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**The Impact of Palustrine Wetland Loss on Flood Peaks: An Application of Distributed Hydrologic Modeling in Harris County, Texas**

by

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# ABSTRACT

The Impact of Palustrine Wetland Loss on Flood Peaks:

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This study uses a distributed hydrologic model to assess the impact of wetland loss on flood peaks. There is large agreement among hydrologists that wetlands have significant flood-mitigation potential. However, the lack of data availability and the appropriate model have generally prevented this impact from being quantified and applied to city planning. From 1980 to 2008 sixty percent of the wetlands in Houston's Cole Creek were destroyed. Because of its proximity to downtown, a wealth of historical, hydrologic data are available for the subbasin. Distributed hydrologic models, which have become more accessible with the increase of computer processing power, allow for the consideration of finite areas, such as wetlands, on watershed response. This study found that wetland loss from 1980 to 2008 has increased flood peaks by approximately 15 percent in Cole Creek, for 2, 5, and 10-year storms.

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# 1. Introduction and Background

Wetlands occupy approximately nine percent of the world's land and five percent of the contiguous United States, but provide a disproportionate amount of services relative to their size (Zedler & Kercher, 2005). Among these services are the many roles they play within the hydrologic cycle. In flood prone urban areas wetlands can serve to reduce flood peaks (Bullock & Acreman, 2003). However, urbanization is the largest force in wetland loss, thus exacerbating potential flood problems (Zedler & Kercher, 2005). Despite the general agreement among hydrologists regarding the hydrologic impact of wetlands, it has been difficult to quantify the impact that wetlands have on flood relief and other aspects of the hydrologic cycle. This thesis develops a method which quantifies the impact of wetland loss on flood peaks and identifies key mitigating wetlands. This method is then applied to Houston's Cole Creek subbasin, which provides a representative case study because of subbasin wetland distribution and loss trends from 1980 to 2008.

Wetlands provide critical ecosystem services such as stormwater quality improvement and flood peak reduction, biodiversity support, and carbon sequestration (Zedler & Kercher, 2005). Mitsch and Gosselink (2000) generally state that regions composed of three to seven percent wetlands optimize on their capability to treat water and reduce flood peaks. Hey and Philippi (1995) propose that the increase in annual flooding in the upper Mississippi Basin is predominantly due to wetland loss. It has been found that wetlands provide further benefit by removing solids, nutrients, organics, metals, and pathogens from water (Kadlec & Knight, 1996). The presence of wetlands supports high plant productivity which in turn attracts a high number of animal species (Zedler &

Kercher, 2005). Wetlands also offer a disproportionately large amount of carbon storage relative to their small surface area (Mitra, Wassmann, & Vlek, 2005).

Though wetlands can provide necessary ecosystem services to urban and suburban areas, the very nature of development threatens their existence. Brody et al. (2008) correlated federal wetland alteration permits with the National Wetlands Inventory data to gain a better understanding of Texas state trends concerning wetland loss. They suggest that loss in Texas is primarily due to urban sprawl through small developments centered around Houston and Corpus Christi. However, given the projected population growth along the Texas coast, predominantly natural watersheds could start to see increasing development and wetland loss.

Given the hydrologic services that wetlands provide and the anticipated growth along the Texas coast, it is critical to create watershed models and decision making criteria to identify hydrologically influential wetlands prior to development. In the past creating such models has proven difficult because of the lack of available modeling techniques and data. However, advances in hydrologic modeling, GIS, and the availability of good data has enabled much needed research regarding the impact of wetlands on the hydrologic cycle over time (Liu, Yang, & Wang, 2008; Said, Ross, Trout, & Zhang, 2007; Sun, Riekerk, & Comerford, 1998; Wang et al., 2010; Wu & Johnston, 2008). Still, only a few studies have focused on the impact of wetlands on watershed hydrology during single-storm events (Kazezyılmaz-Alhan, Medina, & Richardson, 2007; McKillop, Kouwen, & Soulis, 1999; Yu, Wang, Yang, & Kuo, 2006).

Many modeling techniques fail to assess the impact that wetlands can have on flood peaks because they fall short in addressing at least one of the following areas: complex, intra-subbasin, spatial relationships; appropriate time-steps; and unique aspects of wetlands surface hydrology. The following discussion considers these hurdles and details the efforts that have been made to model wetlands within a watershed environment.

A large number of the wetlands-incorporating watershed models have been created using semi-distributed models (Liu et al., 2008; Said et al., 2007; Wang et al., 2010; Wu & Johnston, 2008). This modeling approach is often chosen because of the wide use and acceptance of freely available models such as Hydrological Simulation Program – FORTRAN (HSPF), Soil and Water Assessment Tool (SWAT), and others. These modeling efforts have focused on adapting existing models to incorporate the impact of wetlands on watershed hydrology. For example, Said et al. (2007) devised a method using a storage-attenuation relationship to account for wetlands' impact on flow in HSPF. Liu et al. (2008) created a SWAT module which allows users to consider the impact that wetlands have on runoff. Inherent in the use of a semi-distributed model is that subbasins can technically contain only one wetland (Liu et al., 2008). Though this approach can yield accurate results through calibration, it may not be as capable as a distributed model in capturing the complexities of wetlands' impact on watershed response. This is because lumped models and semi-distributed models are not able to sufficiently describe the unique spatial relationships between a wetland and its surrounding watershed.

A smaller number of studies have used a fully-distributed model to incorporate wetlands within a watershed. These studies have the potential to more accurately capture the complexities of the spatial relationships within a watershed (Kazezyılmaz-Alhan et al., 2007; Sun et al., 1998). Sun et al. (1998) created the forest hydrological model, FLATWOODS, which considers subsurface and surface flow. This model was specifically developed for application on cypress wetlands. Kazezyılmaz-Alhan et al. (2007) created the distributed model Wetland Solute Transport Dynamics (WETSAND), which models wetland flow using the diffusion wave theory. The model was applied to predict the impact that restored wetlands would have on the Sandy Creek Watershed in Duham, NC. This thesis follows in the steps of Kazezyılmaz-Alhan et al. (2007) and Sun et al. (1998) by modeling wetlands in a larger watershed environment using a distributed model.

The second hurdle that modelers must overcome in order to consider the impact of wetlands on flood peaks is that many models are written to consider time steps of days (Liu et al., 2008; Said et al., 2007; Sun et al., 1998; Wang et al., 2010; Wu & Johnston, 2008). Larger time steps are a perfectly acceptable approach when considering water-budgets and long-term hydrologic trends. However, when considering single-storm events, time steps should be on the order of minutes, not days, in order to capture the specifics of hydrograph timing. Though they do not compare their results to actual flows, Liu et al. (2008) present coarsely-modeled hydrographs from a single storm event modeled in SWAT using a one day time step. In contrast to the general trend, McKillop et al. (1999), Yu et al. (2006), Kazezyılmaz-Alhan et al. (2007) all used small enough time steps to accurately model individual storms. It does not, however, appear that any of the three preceding models are currently available for public application.

The model used for this study—Vflo™ a distributed physics based hydrologic model—uses a model-specific time step calculated using the Courant condition. The Courant condition forces the time step to be less than the travel time across an individual element (Vieux, 2004):

$$\Delta t = \frac{L}{\sqrt{gh}}. \qquad \text{(Eq. 1)}$$

In this equation $\Delta t$ is the maximum time step, $L$ the element size, $g$ acceleration due to gravity, and $h$ flow depth. Vflo™ uses the maximum individual-cell, flow depth throughout a storm and then multiplies it by a factor of safety to make sure the time step is not too large. In practice, for this study, the Courant condition results in a time step on the order of seconds or minutes.

The final hurdle in modeling wetlands within a watershed environment is the fact that there is not an easily-defined relationship between the type of wetland and its hydrologic performance. One cannot simply classify a wetland and presume to have an accurate understanding of its hydrology. In practice wetlands must be considered on a case by case basis. For example, some wetlands have a significant surface water-groundwater connection, while other wetlands of the same type exhibit no such connection (Bullock & Acreman, 2003).

Modeling wetlands is further complicated by the fact that wetlands modelers generally do not accept the use of Manning's equation, an industry standard, to model overland flow in wetlands (Kadlec, 1990; Kadlec, Hammer, Nam, & Wilkes, 1981; Kazezyılmaz-Alhan et al., 2007; McKillop et al., 1999). The reason for this is twofold. First, wetlands flow is usually laminar or transitional, while Manning's equation was developed for turbulent flow. Second, the primary friction force present in wetlands is from vegetation stems, while Manning's equation is based off of bed roughness. Kadlec and Knight (1996) propose replacing Manning's Equation with the Wetlands Power Law. However, the predominant models used do not incorporate this method.

As noted, a number of studies have worked to incorporate wetlands into semi-distributed models. Said et al. (2007) incorporated wetlands into HSPF as reach reservoirs using a storage-attenuation relationship to define flow. Liu et al.'s (2008) SWAT module considers riparian and isolated wetlands. In their module riparian wetlands receive the output from the subbasin, while isolated wetlands can be routed to the riparian wetland or directly to the stream. This module relies upon SWAT's equations for water bodies to describe wetlands flow. Only one wetland may be considered in each subbasin as SWAT allows for only one water body in each subbasin. Therefore multiple wetlands are merged and considered as one.

The few published studies (Kazezyılmaz-Alhan et al., 2007; McKillop et al., 1999) that modeled a wetland using a distributed hydrologic model have used Kadlec et al.'s (1981) Wetlands Power Law to account for surface water velocity in the model. McKillop et al. (1999) used this equation and solved for flow using a mass balance equation. Their model does account for infiltration, but does not expressly incorporate other groundwater interactions. Users, however, are able to specify groundwater inflow during the calibration process. Kazezyılmaz-Alhan et al. (2007) also use a power law relationship to account for velocity, but solve for flow using the diffusion wave equation in their model WETSAND. The model uses the Storm Water Management Model (SWMM5) to determine runoff into the wetland area. Both of these studies do a fine job of modeling wetlands flow. However, it appears that McKillop et al. (1999) have only modeled a wetland, not a wetland within the larger context of a watershed. From Kazezyılmaz-Alhan et al. (2007) it is unclear if the model can be applied at a watershed scale without using inputs from SWMM5, which is not a distributed model. Neither one of these two previous works has incorporated uniquely wetland-oriented cells into a larger, general distributed watershed model.

This study builds upon the work of Kadlec and Knight (1996), Kazezyılmaz-Alhan et al. (2007) and McKillop et al. (1999) by incorporating wetlands into the watershed model using the Wetlands Power Law. The watershed model chosen for this study was Vflo™, a model that has successfully been applied to a number of flood studies throughout the world, including watersheds in the Houston area (Fang et al., 2010; Kim, Kim, & Kim, 2008; Looper, Vieux, & Moreno, 2009; Vieux, Park, & Kang, 2009; Vieux & Bedient, 2004). Vflo™ has the potential to essentially incorporate unlimited wetland cells using wetlands-specific flow equations. This modification can be made while non-wetland cells are still governed by Manning's equation.

Vflo™ is a distributed model developed out of the University of Oklahoma to provide an intuitive, physics-based hydrologic modeling experience. The model routes flow one dimensionally using the kinematic wave equation (Vieux, 2004):

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = r - i. \qquad \text{(Eq. 2)}$$

In this equation *h* is flow depth, *u* is velocity, *r* is the rainfall rate, and *i* is the infiltration rate. Velocity is solved using Manning's equation.

Infiltration is calculated using the Green-Ampt method (Vieux, 2004):

$$f = K_s \left(\frac{1-\psi\Delta\theta}{F}\right). \qquad \text{(Eq. 3)}$$

In this equation $K_s$ equals saturated hydraulic conductivity, $\psi$ capillary suction, $\Delta\theta$ moisture deficit, and $F$ cumulative infiltration depth. Bedient, Huber and Vieux (2008) note that all of these parameters can be derived from soils data, and thus the method does not require separate infiltration studies.

Each cell within Vflo™ is tied together through a stream network represented by a flow direction grid, which is derived from a digital elevation model (DEM) (Figure 1). The model solves for flow at each cell and time step using a combination of the finite element method and implicit finite difference method. More information regarding Vflo™ can be found in Gourley and Vieux (2006), Kim et al. (2008), and Vieux (2004).

Using the kinematic wave equation to describe flow in wetlands departs from the more traditional, diffusion wave theory, used by Kazezyılmaz-Alhan et al.'s (2007). Generally kinematic wave is not accepted by wetlands modelers because the typically low wetland slopes (0.01-0.1 percent) could cause violation of method assumptions. However the wetland slopes within Cole Creek, the study area, are closer to 0.4 percent. These slopes are similar to watershed slopes throughout the Houston region to which Vflo™ and thus the kinematic wave equation has been applied successfully (Vieux & Bedient, 2004).

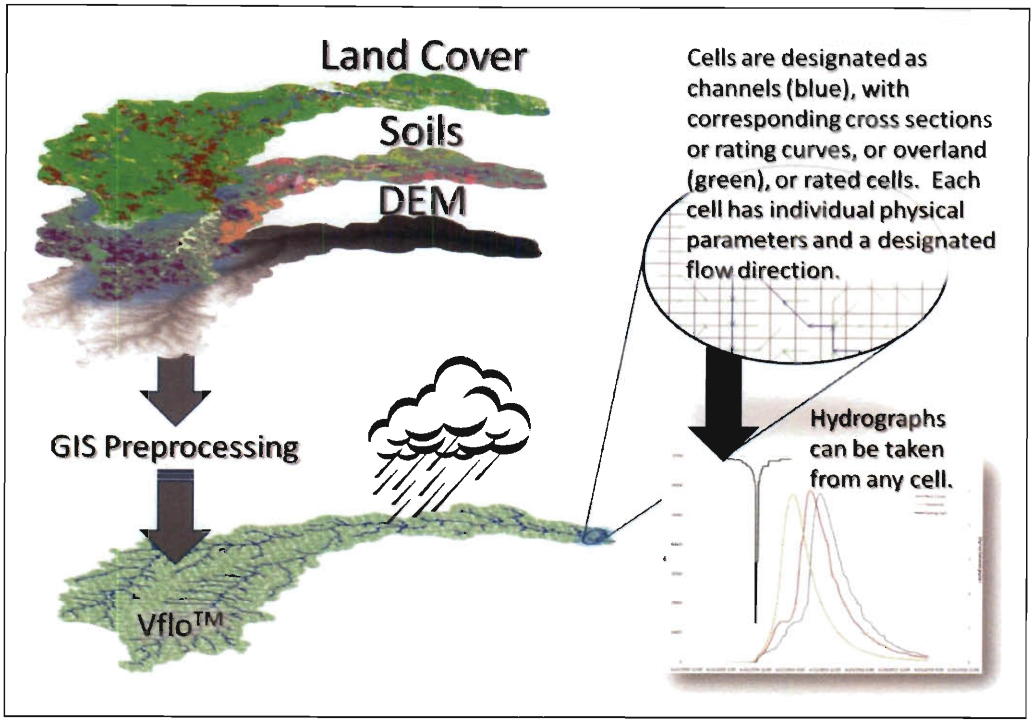


**Figure 1. Overview of Modeling Using Vflo™**

Using Green-Ampt allows the modeler to consider infiltration but does not consider groundwater discharge. However, this work avoids the complexities presented by potential groundwater discharge by focusing on storm events. Any surface water flow would be orders of magnitudes higher than the groundwater contribution, negating the need to focus on ground water contributions.

In summary, this study focuses on incorporating palustrine wetlands into an event-focused, distributed, hydrologic model. The benefit of this approach is that focusing on single-storm events, in contrast to models that focus on the long-term (Said et al., 2007; Sun et al., 1998; Wang et al., 2010; Wu & Johnston, 2008) allows for the consideration of the wetlands' impact on flood peaks. Using a distributed model takes into account the impact that wetland location can have on the overall watershed response. This study differs from other studies which used a distributed model (Kazezyılmaz-Alhan et al., 2007; McKillop et al., 1999; Yu et al., 2006) in that it considers wetland loss that occurred between 1980 and 2008 in the calibration process. In order to gain this historical perspective, a model was created and calibrated for each of the two time periods, the early 1980s and late 2000s. Each model incorporates wetlands in a similar fashion. The only difference between the two models is that the late 2000s model accounts for changes in land use, specifically regarding wetland loss from 1980-2008. By comparing peak flows from design storms, this approach provides a unique perspective on the impact of wetlands on watershed hydrology. The study also compares wetland modeling results obtained using both Manning's Equation and the Wetlands Power Law.

# 2. Materials and Methods

## 2.1. Study Area

White Oak Bayou's Cole Creek, which has an area of about 19 square kilometers, is located 15 kilometers northwest of downtown Houston (Figure 2). The subbasin has mild slopes, generally around one percent (Figure 3), and loamy soils. As Houston is located near the Gulf of Mexico, the area frequently experiences high levels of precipitation and flooding from hurricanes and tropical storms. Annual precipitation averages over 135 centimeters (NWS, 2010).

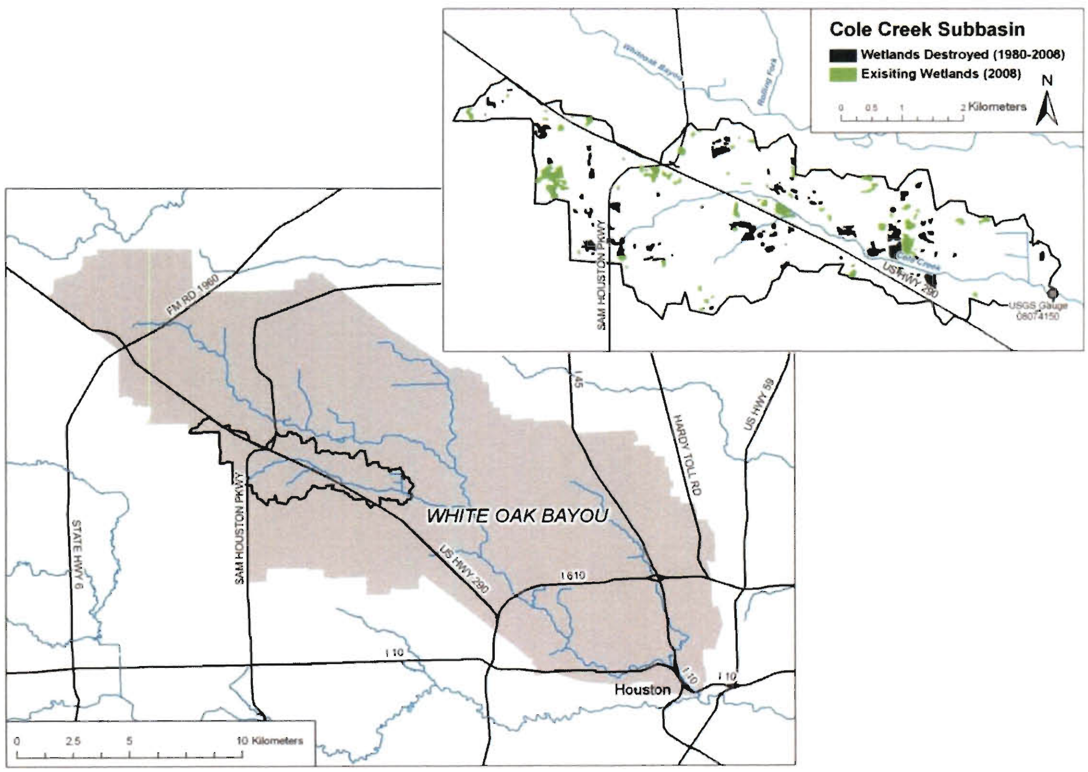


**Figure 2. Cole Creek Location and Wetland loss (1992-2008) (Created from Jacob & Lopez, 2005)**

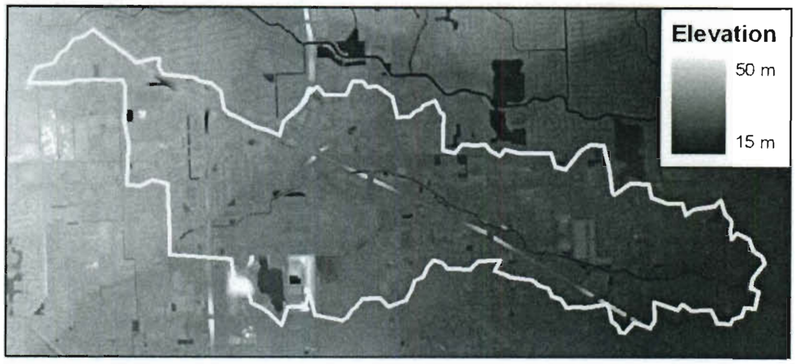


**Figure 3. Cole Creek Elevation**

Cole Creek was selected for this study because it exhibited two qualities. First, it serves as a good representative subbasin to test the notion of flood control via wetlands. Second, it has been well monitored throughout the last 30 years. While there are three subbasins in Harris County, Texas that met the first criterion, one in Greens Bayou and the other in Cypress Creek, only Cole Creek met both of them.

Cole Creek serves as a good representative subbasin to test wetlands flood control for the following reasons:

- The percent wetands in the subbasin is close to both U.S. and global averages. In 1980 the subbasin was made up of approximately seven percent wetlands, in between the global average of nine percent and the contiguous United States average of five percent (Zedler & Kercher, 2005). However, 2008 wetlands composition in the subbasin had fallen to around three percent.
- As nearly 60 percent of the wetlands were destroyed during this time period, their hydrologic significance should be apparent. The loss of wetlands during this time period allows for a straightforward comparison of conditions. If wetlands have

had a sizable impact on flood control, it would be expected that there would be a noticeable impact on flood hydrographs over this period of time.

- The wetlands in Cole Creek are distributed throughout the subbasin and are not just concentrated in small areas.
- Cole Creek is located in a flood prone area.

A variety of data regarding Cole Creek are available from the following sources. The United States Geological Society (USGS) has flow data and rain data for Cole Creek dating back to the mid 1960s. The Harris County Office of Homeland Security and Emergency Management (HCOEM) has rain gauge data for at least three gauges surrounding the subbasin from 1986 on (see Section 3.1 and Figure 6). The Houston-Galveston Area Council (H-GAC) published a 2008 land cover data base (2010). Land cover for 1980 is obtainable using Landsat data and the USGS 1992 National Land Cover Dataset (USGS, 2000). John Jacob of Texas A&M made available updates on Jacob and Lopez (2005), which is a database, created from the National Wetlands Inventory (NWI), containing a wetland loss timeline from 1992-2008. Finally, U.S. Fish and Wildlife made available the original aerials and wetlands delineations of northwest Harris County used to create the 1984 National Wetlands Inventory.

## 2.2. Land Development

### 2.2.1. General Land Cover

As previously stated, 2008 land cover was obtained from H-GAC (2010). Land cover for 1980 was derived using 1992 land cover data (USGS, 2000) and Landsat Multispectral

Scanner System (MSS) data from December 18, 1980 and October 26, 1992 using the following steps:

1. A principal component analysis (PCA) was performed on all available bands for each Landsat image. A PCA allows the user to consolidate trends in the data into one or more bands. This is done by aligning the input from each band along an individual axis. The axes are then realigned with the best-fit vector of the data from each band. The user can designate the number of realigned axes outputs as primary, secondary, tertiary, etc (ERDAS, 2008). For this study only the primary output was considered.
2. Change detection was performed on the PCA output from each image to detect a plus/minus 10 percent change in value. Change detect was also attempted at 20 and 50 percent. The differences between all three outputs were negligible.
3. The output from the change detection was overlaid upon the 1992 National Land Cover Dataset (USGS, 2000). Regions that indicated change were then reclassified using aerials from 1980.

The results of this classification are shown in Figure 4 and Table 1.

From 1980 to 2008 the subbasin experienced a large amount of development. In 1980 the area was largely composed of agricultural lands, with a sizable percentage of residential and high-intensity development. By 1992 large sections of the subbasin had been developed into low and high-intensity development, centering largely around Highway 290 and Beltway 8. Any cultivated areas remaining in 1992 were all destroyed by 2008. At this point high and low-intensity development had grown to encompass 90 percent of the subbasin. For all time periods this high-intensity development was centered around US Highway 290.

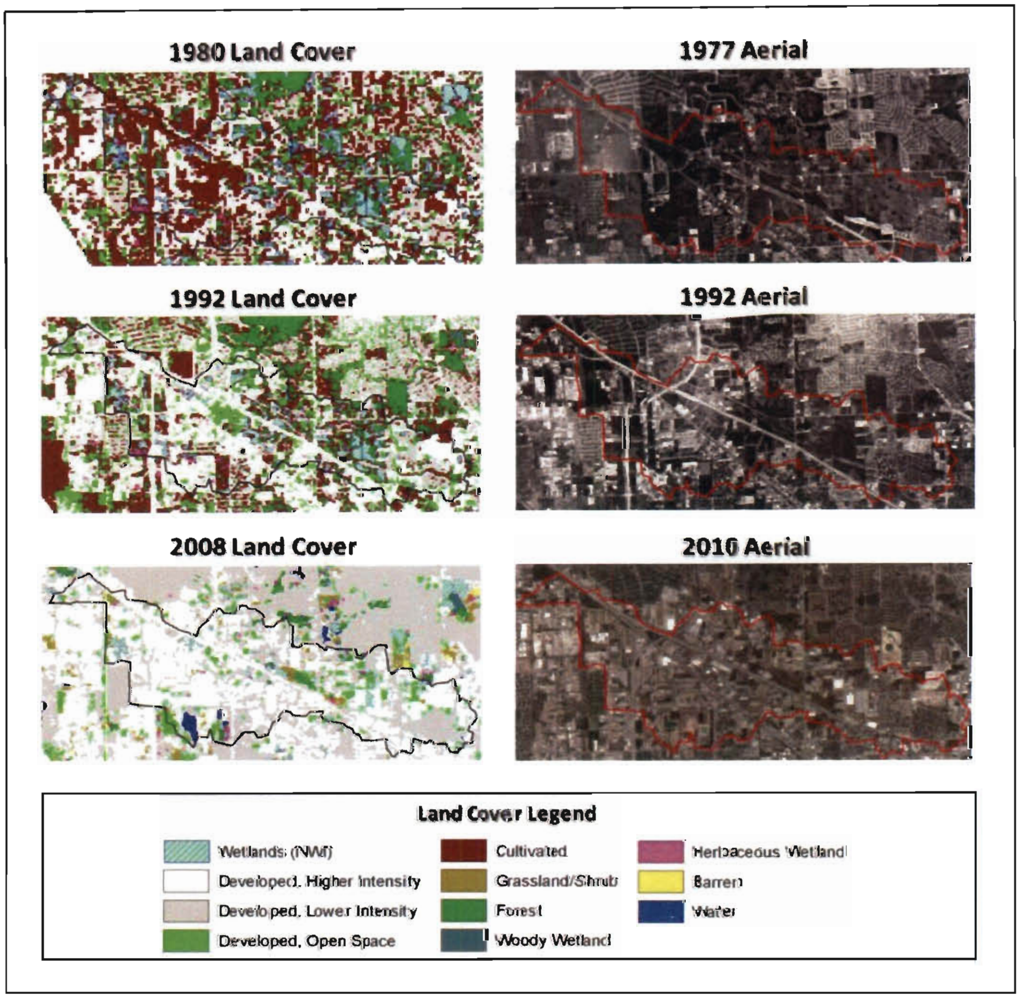


**Figure 4. Cole Creek Land Cover**

**Table 1. Cole Creek Land Development (1980-2008)**

| Land Cover | Percent Land Cover (1980) | Percent Land Cover (2008) (H-GAC, 2010) |
|---|---|---|
| High-Intensity Development | 24 | 50 |
| Low-Intensity Development | 13 | 40 |
| Open Space Development | 5 | 4 |
| Cultivated | 43 | 0 |
| Undeveloped (e.g. wetland, forest, grassland) | 14 | 5 |
| Other (e.g. water, barren) | 0 | 1 |

### 2.2.2. Wetlands Area

Wetland delineations for 1980 and 2008 were both derived from the NWI. The wetlands used in the 1980 model were from the 1992 NWI. The 1992 NWI was chosen over the 1984 NWI because it offered a more extensive wetlands inventory. Many of the wetlands in the 1992 inventory were not present in the 1984 inventory. However, most of the wetlands in the 1984 inventory were present in the 1992 inventory. Since the land cover change between 1980 and 1992 generally involved the conversion of agricultural lands to residential lands, it is assumed that most of these agricultural lands did not contain wetlands and thus not many wetlands were destroyed between 1980 and 1992. Hence forth wetlands delineated in the 1992 NWI will be referred to as the 1980 wetlands in order to correspond with their respective hydrologic model.

The only large group of wetlands from the 1984 inventory that the 1992 inventory did not contain was a group of riparian wetlands—which are wetlands that are situated along stream banks—centered around the southern branch of Cole Creek. Still these riparian wetlands were not used because while palustrine wetlands, isolated inland wetlands, can be modeled as individual cells, riparian wetlands must be incorporated into the channel themselves. Given that Vflo$^{TM}$ does not have the ability to vary Manning's roughness or the modeling approach across a channel cross section. Accordingly, Vflo$^{TM}$ is not able to model riparian wetlands. For this reason, this study focuses on the impact of palustrine wetlands.

Wetland delineations for 2008, as stated in Section 2.1, were taken from an updated version of Jacob and Lopez (2005). This database is based on the 1992 NWI documenting a timeline of wetland loss from 1992-2004. Since publication they have updated this database for 2008 as well. The 2008 version was used for this model.

In 1980 wetlands made up approximately seven percent of the subbasin or 130 hectares. By 2008 the wetlands area fell to 54 hectares, or three percent of the total subbasin area. (Jacob & Lopez, 2005). Thus, the wetlands area from 1980 to 2008 dropped by nearly 60 percent. For both 1980 and 2008, the majority of these wetlands were forested, with the remaining wetlands classified as scrub-shrub and emergent (Table 2). From a field survey of existing wetlands, it appears that most of the wetlands classified as emergent would more accurately be described as forested or scrub-shrub.

The average size of individual wetlands remained relatively stable throughout time. The 1980 wetlands had a mean of 0.8 hectares, a maximum of 7.3 hectares, and a standard deviation of 2.8. The 2008 wetland size had a mean of 0.6 hectares, a maximum of 7.3 hectares, and a standard deviation of 2.5.

**Table 2. Deihl Subbasin NWI Wetlands Classification (Created from Jacob & Lopez, 2005)**

| NWI Wetland Class | 1980 (ha) | 1980 (% Wetlands Area) | 2008 (ha) | 2008 (% Wetlands Area) |
|---|---|---|---|---|
| **Forested** | Temporarily Flooded- 87.5<br>Seasonally Flooded- 16.5<br>**Total- 104.0** | **79.9** | Temporarily Flooded- 24.9<br>Seasonally Flooded- 9.9<br>**Total- 34.8** | **65.0** |
| **Scrub-Shrub** | Temporarily Flooded- 13.0<br>Seasonally Flooded- 1.7<br>**Total- 14.7** | **11.3** | Temporarily Flooded- 9.4<br>Seasonally Flooded- 1.2<br>**Total- 10.6** | **19.8** |
| **Emergent** | Temporarily Flooded- 9.3<br>Seasonally Flooded- 2.1<br>Semipermanently Flooded- 0.1<br>**Total- 11.5** | **8.8** | Temporarily Flooded- 6.4<br>Seasonally Flooded- 1.6<br>Semipermanently Flooded- 0.1<br>**Total- 8.1** | **15.1** |

### 2.2.3. Runoff:Rainfall Coefficient Comparison

Though it is obvious that the subbasin has experienced a large amount of development from 1980 to 2008, it is critical to this study that these effects be evident hydrologically. In order to assess the impact of wetland loss on flood peaks over a period of time, there must be an evident increase in flood peaks. Subbasin development is often apparent to hydrologists through the ratio of stormwater runoff to total rainfall. This ratio gives an indicator of how much rain is being converted to runoff and how much is infiltrating into the soil. More developed watersheds generally do not allow as much water to infiltrate and thus have higher runoff to rainfall ratios. Runoff to rainfall ratios for Cole Creek from different time periods were developed from similar sized storms and compared. The results confirmed that subbasin development was indeed having a significant hydrologic effect (Table 3). On average these ratios increased by 0.13 from 1980 to 2008. This increase in runoff shows similar trends to a larger sampling of 17 storms from 1979 to 2009, during which runoff to rainfall ratios increased from 0.40 to 0.48.

**Table 3. Runoff:Rainfall Coefficients**

| Date | Rainfall (mm) | Runoff (mm) | Runoff:Rainfall Ratio | Average |
|---|---|---|---|---|
| March 29, 1980 | 111 | 64 | 0.58 | 0.36 |
| April 23, 1981 | 53 | 15 | 0.28 | |
| October 6, 1981 | 78 | 17 | 0.21 | |
| October 15, 2007 | 108 | 61 | 0.56 | 0.49 |
| November 19, 2007 | 91 | 42 | 0.46 | |
| August 5, 2008 | 67 | 25 | 0.38 | |
| November 12, 2008 | 47 | 27 | 0.57 | |

## 2.3. Model Development

Most Vflo™ inputs, which are taken from from elevation, land cover, and soils data, require GIS preprocessing. The 1980 and 2008 models in this study were both based on the same elevation and soils data. However, the land cover was unique for each model.

Elevation data provides the cell slope, cell flow direction, and channel cross-sections. Digital elevation models (DEM) can be directly uploaded to Vflo™ Version 5, which in turn extracts all of this information. Vflo™ gives the user the option to force the flow direction to follow known channels and watershed boundaries. For this study the DEM used was from the USGS National Elevation Dataset and had a 30 meter resolution (2010). Flow direction was forced to follow channels provided by the USGS National Hydrology Dataset (1999) and a watershed boundary provided by the Houston-Galveston Area Council (H-GAC) (2007).

A separate, more-accurate DEM, with a resolution of one meter, was used to cut channel cross-sections (H-GAC, 2008). This DEM was not used to calculate flow direction and slope because of the large processing time required for high resolution data. Cells that have a contributing area in the top 10 percent were designated as channel cells.

Soils data were retrieved from the National Resource Conservation Service's (NRCS) Soil Data Mart (2004). This dataset was preprocessed using ArcGIS to determine Green-Ampt infiltration parameters, which were then imported into Vflo™. The Green-Ampt soil parameters required for Vflo™ are hydraulic conductivity, wetting front capillary pressure, effective porosity, initial saturation, and soil depth.

Hydraulic conductivity and wetting front capillary pressure were derived by correlating the Soil Data Mart listed USDA soil type with respective values in Rawls, Brakensiek, and Miller (1983). They list loam as having a hydraulic conductivity of 0.34 cm/hr and capillary pressure of 8.89 cm.

Effective porosity and initial saturation were derived by correlating the USDA soil type with respective values in Rawls, Brakensiek, and Saxton (1982). For a loam soil they list effective porosity to be 0.434. Initial saturation for each soil type was assumed to be the same as the saturation present after gravity drainage under 33 kPa, which is 0.270.

Soil depth was assumed to equal the thickness of the top layer of soil in Soil Data Mart. This is the only soils parameter that varied throughout the subbasin. Values for depth range from 27.94 cm to 40.64 cm. The average value throughout the subbasin is 30.06 cm.

Land cover was retrieved from H-GAC and Landsat as discussed previously. These data were used to create raster files of roughness and percent imperviousness, which were then imported into Vflo™. Table 4 gives the correlated Manning's roughness and percent imperviousness for each land cover category.

**Table 4. Land Cover Modeling Parameters**

| Land Cover | Manning's Roughness | Percent Imperviousness (TSARP, 2003) |
|---|---|---|
| Developed, Higher Intensity | 0.015 (Vieux, 2004) | 85% |
| Developed, Lower Intensity | 0.015 (Vieux, 2004) | 40% |
| Developed, Open Space | 0.05 (Vieux & Associates, Inc., 2010) | 15% |
| Cultivated | 0.035 (Vieux, 2004) | 0% |
| Grassland/Shrub | 0.04 (Vieux & Associates, Inc., 2010) | 0% |
| Forest | 0.1 (Vieux, 2004) | 0% |
| Woody Wetland | 0.06 (Vieux & Associates, Inc., 2010) | 0% |
| Herbaceous Wetland | 0.055 (Vieux & Associates, Inc., 2010) | 0% |
| Bare | 0.04 (Vieux & Associates, Inc., 2010) | 0% |
| Open Water | 0.015 (Vieux & Associates, Inc., 2010) | 100% |

## 2.4. Wetlands Modeling

As discussed in Section 1, wetlands hydrologists generally prefer the Wetlands Power Law over Manning's equation. The Wetlands Power Law as given by Kadlec and Knight (1996) is

$$u = ah^b S^c, \qquad \text{(Eq. 4)}$$

where $u$ is velocity, $a$ is roughness value (this is not equal to Manning's roughness), $h$ is water depth, $S$ is slope, and $b$ and $c$ are parameters which are adjusted depending on the scenario (e.g. open channel, sheet flow). If a is $1/n$, $b$ is 5/3, and $c$ is 1/2, then the equation is identical for Manning's equation for sheet flow. However, $b$ and $c$ are generally set to three and one, respectively. As $b$ is adjusted down from this value the impact of stem roughness drops off faster with depth, approaching more channel-like conditions. Also, notice that when $c$ equals one and $ah^b$ equals $K$ the Wetland Power Law is the same as Darcy's Law for groundwater flow. This relationship is indicative of the fact that wetlands flow, like groundwater, is usually laminar.

Using the Wetlands Power Law with the recommended inputs assures that the effects from friction will not drop off prematurely with depth. It therefore provides a more accurate representation of wetlands friction; while when Manning's equation is used friction effects generally drop off too rapidly as depth increases. Thus to use Manning's, roughness must be adjusted as a function of depth.

Kadlec and Knight (1996) recommend using $a$ values of $1 \times 10^7\ m^{-1}d^{-1}$ for densely vegetated wetlands and $5 \times 10^7\ m^{-1}d^{-1}$ for wetlands with sparse vegetation. After a field survey it was decided that all of the wetlands in this study would be modeled as densely vegetated. A unique rating curve was created for each wetland cell given the cell specific slope.

The Wetlands Power Law can be implemented in Vflo$^{TM}$ using rating curves. Vflo$^{TM}$ allows for each cell to be described as an overland-flow cell, a channel cell, or a detention cell. Channel cells can be further described as using cross sections or rating curves. Detention cells are also described using rating curves. In this study wetlands have been described as rated, channel cells as opposed to detention cells. Rated, channel cells were chosen because they are routed using the kinematic wave equation rather than level-pool routing, which is used by detention cells. Wetland flow losses to groundwater are incorporated using Green-Ampt.

# 3. Model Calibration

Each model was calibrated to storms in the range of a 2-year event. This level of storm was chosen after a preliminary analysis which used a Manning's roughness value of one to model wetlands. The results of this analysis showed that wetlands would have minimal impact on larger storms near the 100-year level and a significant impact on smaller storms near a 2-year level.

Vflo™ allows the user to calibrate the model by adjusting each individual parameter for a given cell or group of cells by a designated multiple. In the end the calibration process led to the creation of four different models: a 2008 model which models wetlands using Manning's equation (Manning's '08), a 2008 model which models wetlands using the Wetlands Power Law (Power Law '08), a 1980 model which models wetlands using Manning's roughness (Manning's '80), and a 1980 model which models wetlands using the Wetlands Power Law (Power Law '80) (Table 5).

**Table 5. Model Overviews**

| Model Name | Land Cover Year | General Overland and Channel Modeling Method | Wetland Modeling Method | Routing Method | Infiltration Method |
|---|---|---|---|---|---|
| Manning's '08 | 2008 | Manning's Equation | Manning's Equation | Kinematic Wave | Green-Ampt |
| Power Law '08 | 2008 | | The Wetlands Power Law | | |
| Manning's '80 | 1980 | | Manning's Equation | | |
| Power Law '80 | 1980 | | The Wetlands Power Law | | |

The Manning's '08 model was calibrated first. Calibrated soils data from the 2008 model were then imported into the Power Law '08 Model and the 1980 models (Figure 5). This was done under the assumption that the soils conditions should generally be the same for each model. The calibration strategy for each model progressed from matching runoff volume, to matching the receding limb of the hydrograph, to finally matching the peak.

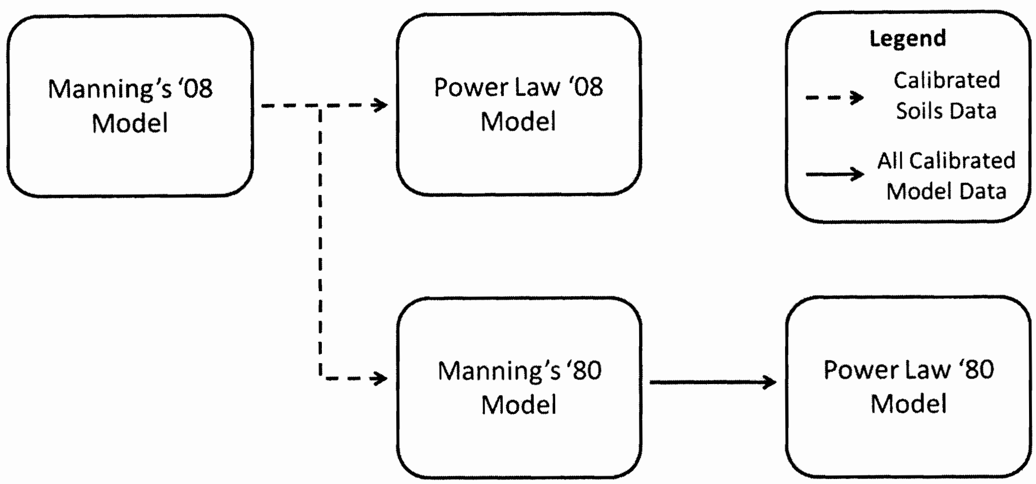


**Figure 5. Model Development**

## 3.1. 2008 Models Calibration

The 2008 model was calibrated to four storms: October 15, 2007; November 18, 2007; August 5, 2008; and November 12, 2008. Rain gauge data were taken from eight gauges in the subbasin area run by Harris County Office of Homeland Security and Emergency Management (Figure 6). Gauge data for the November 2008 storm were not available for Gauges 540 and 2280.

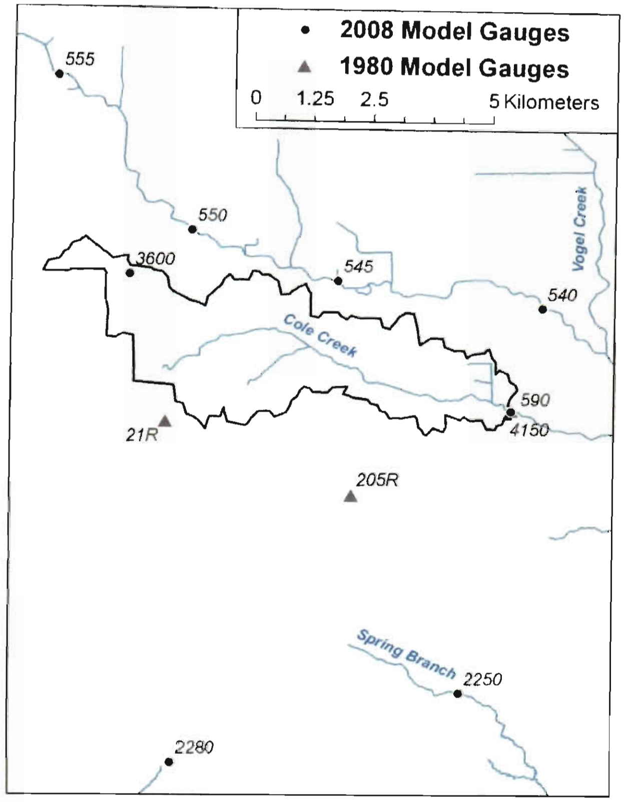


**Figure 6. 1980 (Liscum, Brown, & Kasmarek, 1997) and 2008 (Harris County OHSEM, 2010) Model Rain Gauges**

After the initial model build, several steps were taken to calibrate the Manning's '08 Model. First, hydraulic conductivity was increased by a factor of ten, which is more representative of a sandy loam than a loam. Second, percent imperviousness was reduced by 20 percent. These first two changes were made in order to better match volume. Next, the number of channel cells was reduced to approximately two percent in order to better match peak height and the receding limb of actual storm. Fourth, roughness was increased by 20 percent to reduce and better match peaks. Finally, initial saturation for the November 2008 storm, which was preceded by a wet period, was multiplied by a factor of three.

The final calibration resulted in a wetlands Manning's roughness of 0.072. Wetlands hydrologists generally recommend roughness values orders of magnitude higher (Kadlec & Knight, 1996). However, for consistency with the Manning's '80 Model, 0.072 was used. Higher wetlands roughness values in the Manning's '80 Model greatly degenerated the match.

The Power Law '08 Model was created using calibrated soils data from the Manning's '08 Model. Prior to calibration of the Power Law '08 Model, cell specific wetlands rating curves were inserted into each wetland cell. Calibration was performed in two steps. First, the model channel cells were reduced to five percent. This step enhanced both volume and peak matches. Second, initial saturation was reduced by 80 percent for the October 2007, November 2007, and August 2008 storms. These storms were all preceded by a dry period. Like the Manning's '08 Model the original initial saturation for the November 2008 storm was increased by 300 percent. The changes in initial saturation enhanced peak matches. Output from this model was then compared to the Manning's '08 Model for each storm (Figure 7, Figure 8, Figure 9, and Figure 10).

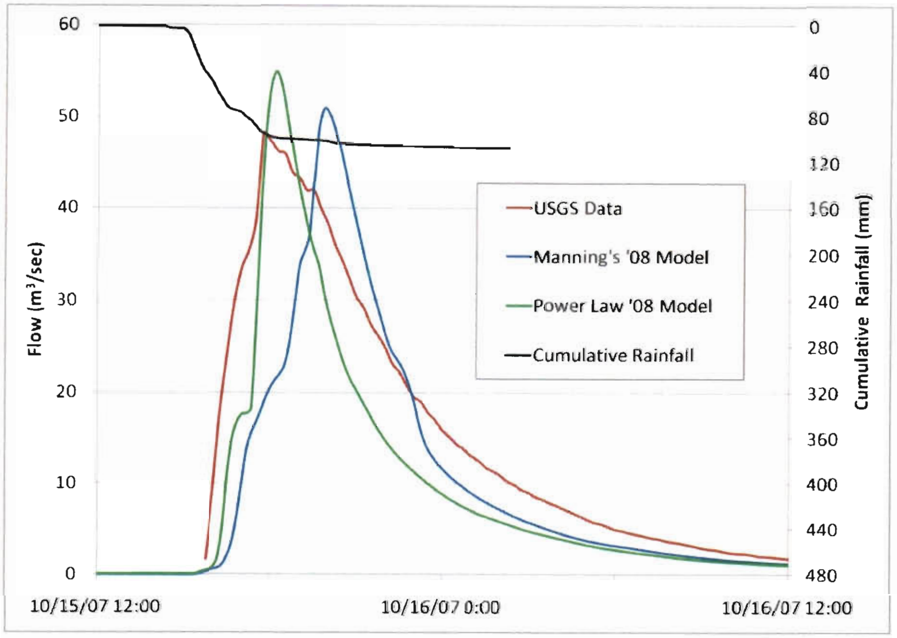


**Figure 7. Cole Creek Hydrograph at Deihl Road: October 15, 2007**

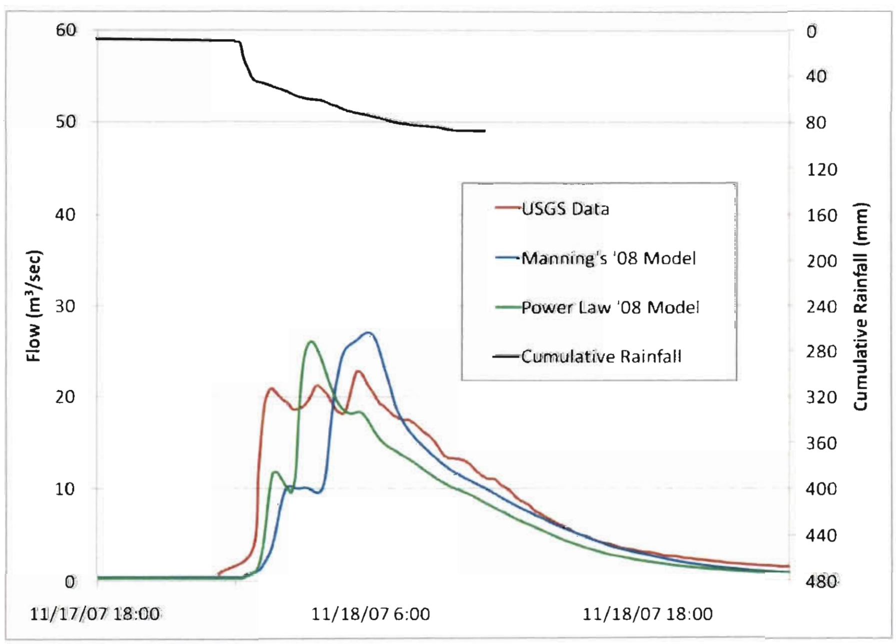


**Figure 8. Cole Creek Hydrograph at Deihl Road: November 19, 2007**

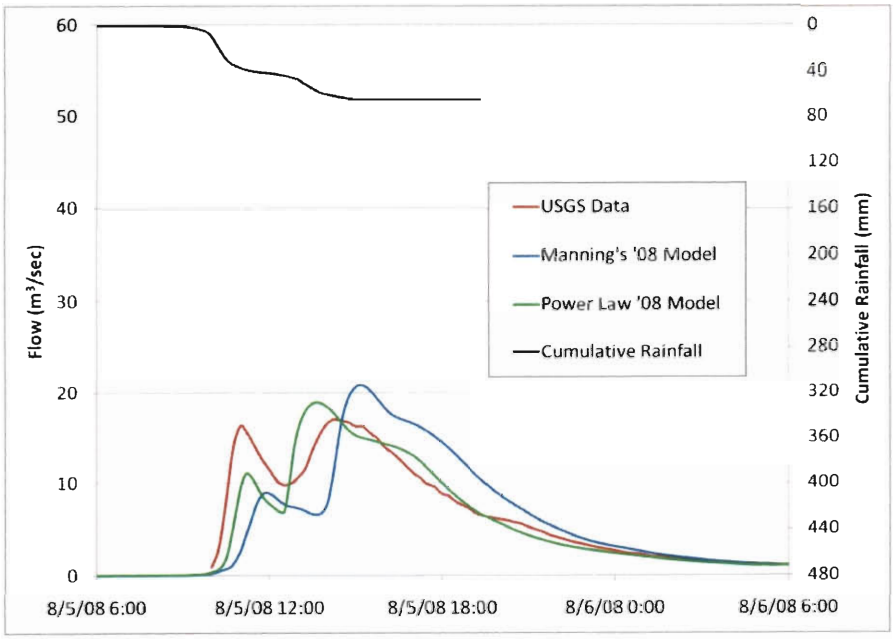


**Figure 9. Cole Creek Hydrograph at Deihl Road: August 5, 2008**

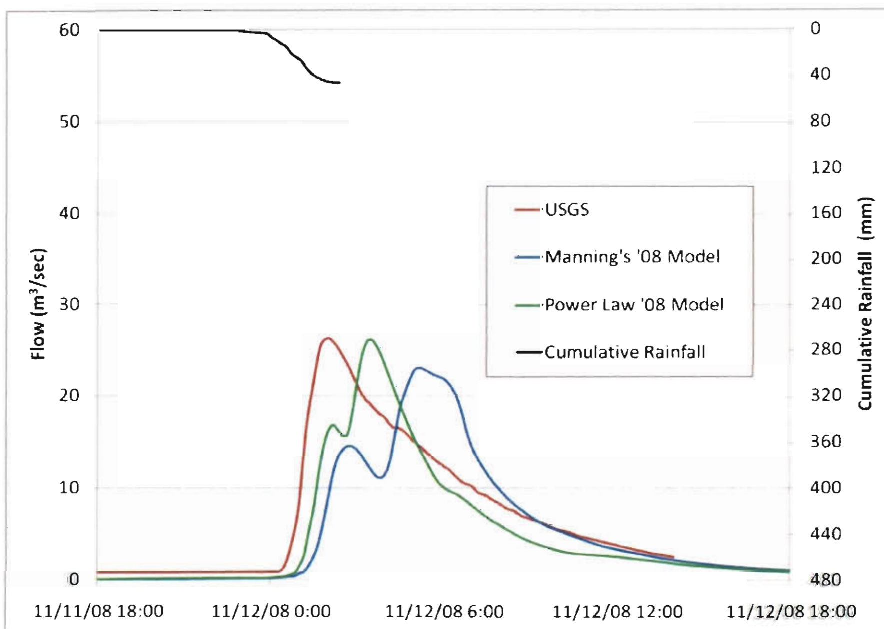


**Figure 10. Cole Creek Hydrograph at Deihl Road: November 12, 2008**

Each model was evaluated according to two criteria, accuracy and consistency, to assess the effectiveness of the calibration and wetlands modeling methods. An ideal model will obviously match observed data every time. However, if a model consistently errors (e.g. over/under predict volume, peak flow, or peak timing), the user could still draw better conclusions than those made from a model with erratic matches. Accuracy and consistency were assessed by visual inspection of the hydrographs, percent error, and standard deviation of the error (Table 6, Table 7, and Table 8). Individual and average percent error give an understanding into the accuracy of the model. The standard deviation of the error gives an understanding of the consistency of the model.

**Table 6. Wetlands Modeling Method Volume Comparison**

| Storm Date | USGS Runoff Depth (mm) | Manning's '08 Model | | Power Law '08 Model | |
|---|---|---|---|---|---|
| | | Runoff Depth (mm) | Error | Runoff Depth (mm) | Error |
| 10/15/07 | 61 | 52 | -15% | 48 | -21% |
| 11/19/07 | 42 | 43 | 2% | 40 | 4% |
| 08/05/08 | 25 | 31 | 26% | 28 | 12% |
| 11/12/08 | 27 | 28 | 3% | 26 | -4% |
| **Average Error** (Using Absolute Values) | - | - | **11%** | - | **11%** |
| **Standard Deviation** | - | - | **17%** | - | **14%** |

**Table 7. Wetlands Modeling Method Peak Flow Comparison**

| Storm Date | USGS Peak Flow ($m^3$/sec) | Manning's '08 Model | | Power Law '08 Model | |
|---|---|---|---|---|---|
| | | Peak Flow ($m^3$/sec) | Error | Peak Flow ($m^3$/sec) | Error |
| 10/15/07 | 48.1 | 50.9 | 6% | 54.9 | 14% |
| 11/19/07 | 22.7 | 27.0 | 19% | 26.1 | 15% |
| 08/05/08 | 17.0 | 20.8 | 22% | 18.9 | 11% |
| 11/12/08 | 26.3 | 23.0 | -12% | 26.2 | 0% |
| **Average Error** (Using Absolute Values) | - | - | **9%** | - | **10%** |
| **Standard Deviation** | - | - | **16%** | - | **7%** |

**Table 8. Wetlands Modeling Method Peak Timing Comparison**

| Storm Date | Observed Time to Peak (h:mm) | Manning's '08 Model | | Power Law '08 Model | |
|---|---|---|---|---|---|
| | | Time to Peak (h:mm) | Difference from Observed (h:mm) | Time to Peak (h:mm) | Difference from Observed (h:mm) |
| 10/15/07 | 1:10 | 3:15 | 2:05 | 1:35 | 0:25 |
| 11/19/07 | 3:00 | 5:15 | 2:15 | 2:45 | -0:15 |
| 08/05/08 | 2:30 | 3:25 | 0:55 | 1:55 | -0:35 |
| 11/12/08 | 1:15 | 4:25 | 3:10 | 2:45 | 1:30 |
| **Average Difference** (Using Absolute Values) | - | - | **2:06** | - | **0:41** |

Both models have similar results regarding volume and peak flow, with around a 10 percent error for each respective category. Each model also has a similar standard deviation of error regarding volume. The peak flows produced by each model are generally higher than observed flows. However, the Power Law '08 Model has more consistent results. The predominant difference between the two models is in timing. The Power Law '08 Model provides a more accurate time to peak. This assessment is also confirmed visually, for the Power Law '08 Model also does a better job at matching the rising limb. Considering volume, peak flow, and timing, it appears that the Power Law '08 Model better matches the observed data.

## 3.2. 1980 Models Calibration

The 1980 models were calibrated to three storms: March, 29, 1980, April 23, 1981, and October 7, 1981. Rain data were taken from three USGS gauges (Figure 6). The Manning's '80 initial model build generally provided a good match to the observed data. However, two changes were made to calibrate the model. First, initial roughness values were decreased by 20 percent. This fine tuned the peaks to within an average error of 16 percent. Second, all wetlands roughness values were set to 0.072 to match the wetlands roughness for the Manning's '08 Model. Adjusting the wetlands roughness did not significantly affect the output of the model, but was done for consistency.

There was an attempt to reduce the percent channel cells closer to the 2008 models levels. However, the reduction of channel cells reduced the peaks and degenerated the match. Accordingly, channel cells were restored to 10 percent. This change also seems to match the reality observed in the field since some channels have been destroyed. During a field survey it was found that the location of a historical USGS gauge had been paved over.

The Power Law '80 Model was created using the Manning's '80 Model as a foundation. The only difference between the two models is the wetlands modeling technique. Output from each 1980 model was then compared to the observed data for each storm (Figure 11, Figure 12, and Figure 13). The results show that each wetland modeling method provides a good match to observed data. Since the different wetlands modeling methods produce nearly identical results, no further statistical methods were employed in the comparison.

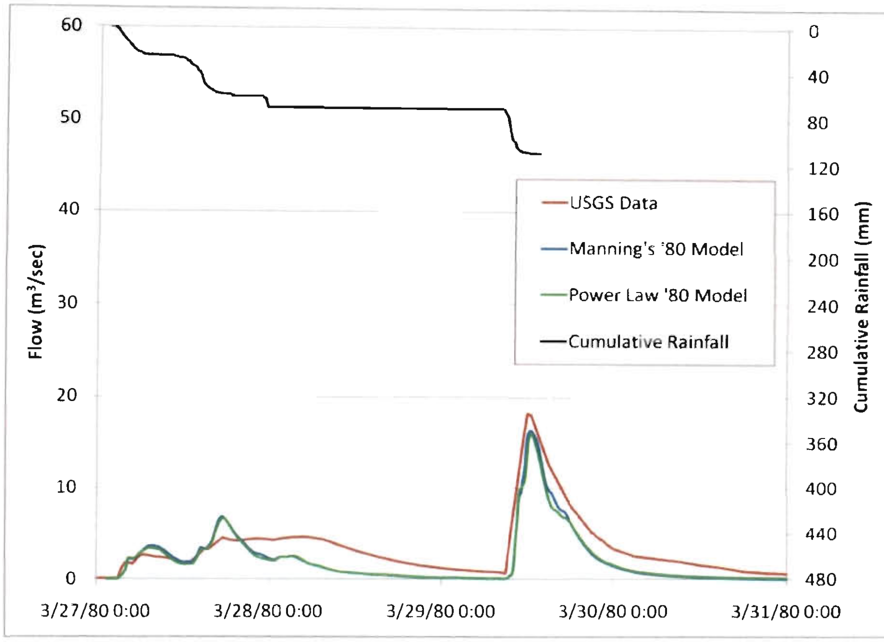


**Figure 11. Cole Creek Hydrograph at Deihl Road: March 29, 1980.**

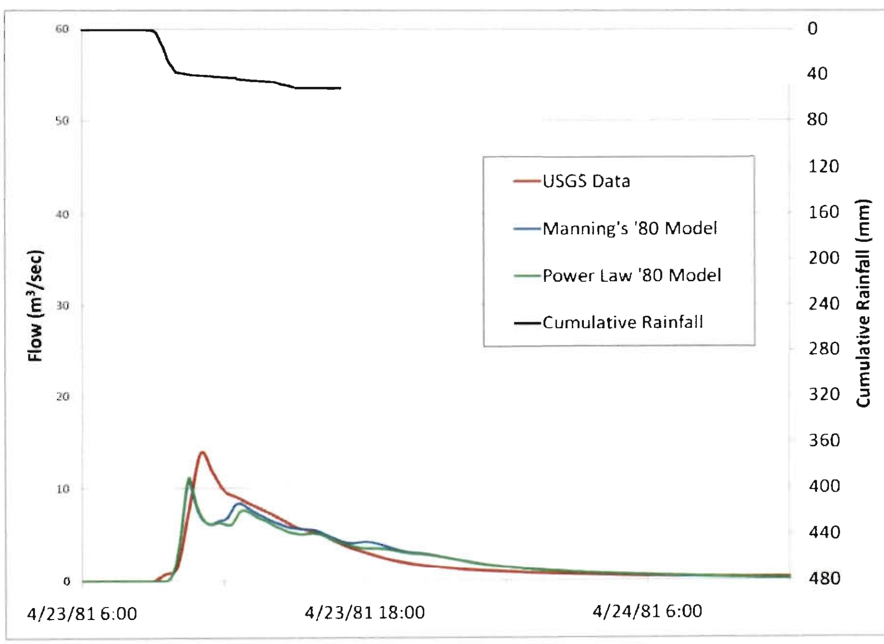


**Figure 12. Cole Creek Hydrograph at Deihl Road: April 23, 1981**

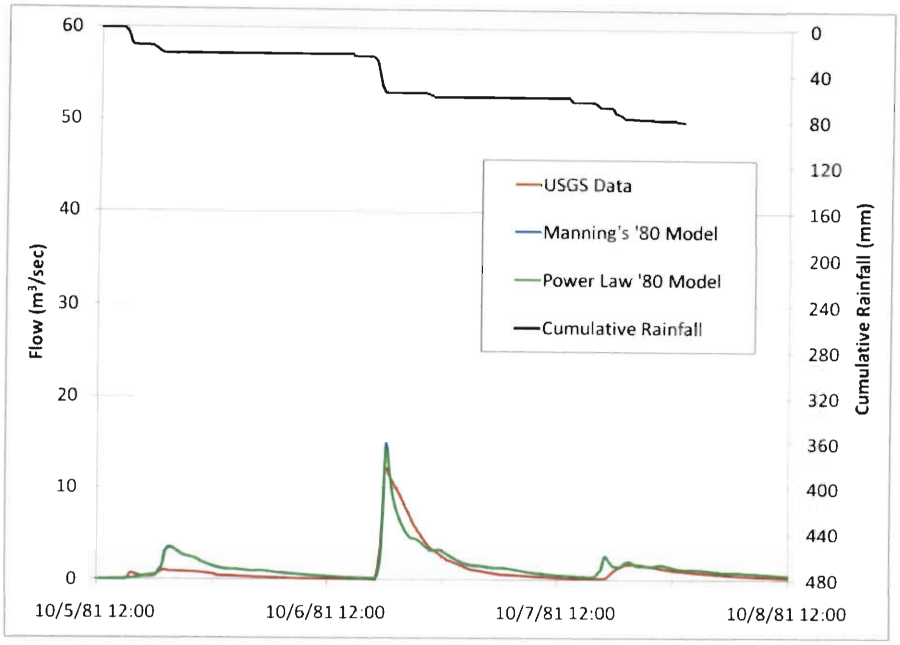


**Figure 13. Cole Creek Hydrograph at Deihl Road: October 6, 1981**

## 3.3. Manning's Roughness versus the Wetlands Power Law

It is interesting to note that while the difference in peaks produced by modeling wetlands using Manning's Roughness and the Wetlands Power Law in 1980 is minimal, the difference is significant for the 2008 models. Though all of the storms used were in the same range, 50-120 mm, flow conditions were much higher in the 2008 model due to subbasin development resulting in a higher flow depth. Wetland cells theoretically should be much more influential in the 2008 model than the 1980 model because the land cover for 2008 is more conducive to higher flow rates; while the land cover in 1980 is generally much more resistant to high flow rates. In the 2008 model wetland cells are generally the only cells which slow down the flow. Contrast this to the 1980 model, when much of the subbasin is quite rough and does not allow for high velocities.

It is also significant that the Manning's '08 Model was unable to reasonably match volume, peak flow, and hydrograph timing. Throughout the calibration process it was possible only to match two of the three. A reasonable match was only reached after wetlands were incorporated using the Wetlands Power Law and the model was recalibrated. From these results it appears that modeling wetlands using the Wetlands Power Law provides a more accurate description of the subbasin hydrology.

# 4. Application to Development Scenarios

Upon calibration of both the 1980 and 2008 subbasin models, it is possible to use them in conjunction as a tool to analyze development scenarios. In this study the models were applied to the following four scenarios:

- A comparison of two hypothetical land cover conditions.
    - In the first condition 1980 wetlands are superimposed on what is otherwise 2008 land cover. This creates a subbasin that has experienced nearly, historical development without any of the wetlands being destroyed.
    - For the second condition all wetlands in the watershed are assumed to be developed, in what otherwise is 2008 land cover.
- A comparison of the flow from two similarly sized zones within the subbasin, one with a high percent wetlands and one with none.
- Identification and assessment of existing wetlands that have the largest potential to reduce flood peaks.
- Identification and assessment of potential wetland construction locations that serve as a gateway to larger drainage areas are identified for potential wetland construction.

These scenarios were all run using the Wetlands Power Law to model wetlands since the Power Law '08 Model proved to be more accurate than the Manning's '08 Model.

In order to visualize the difference in floodplain impact between various flood peaks, floodplains were developed using HEC-RAS under various, flow conditions (Figure 14,

Figure 15, and Figure 16). The HEC-RAS model used was developed for the Tropical Storm Allison Recovery Project (TSARP) (2010). Though not developed for specific application with this project it should nonetheless provide a reasonable estimate. HEC-RAS flow inputs were taken from the Manning's '08 Model using the specified, 24-hour, design storm.

For ease of map use, all percent flow differences in this section are in reference to 2008 flows unless otherwise stated. This section will primarily focus on the 5-year storm since it is close to the size of storm the models were calibrated for and changes in 5-year flow have the potential to impact the flood plain.

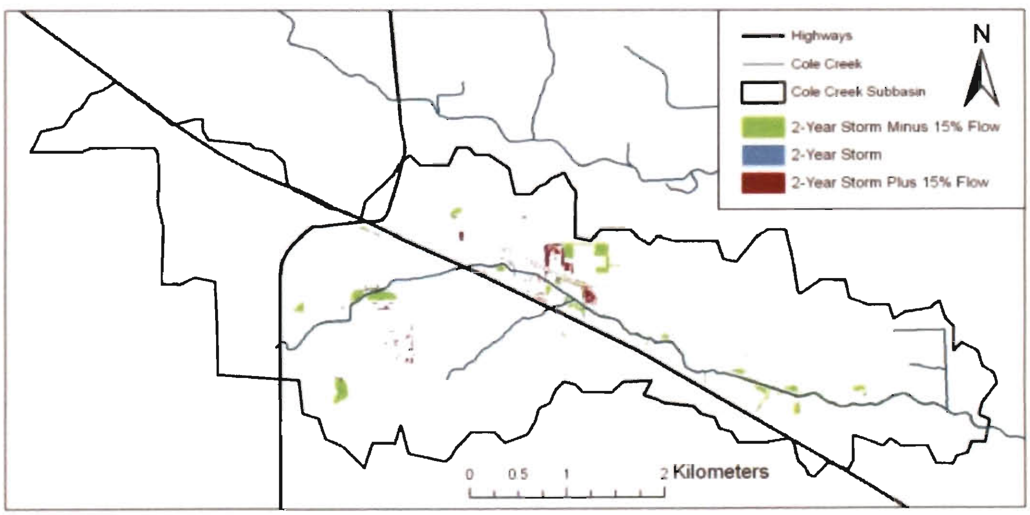


**Figure 14. 2008 2-Year Floodplain Scenarios**

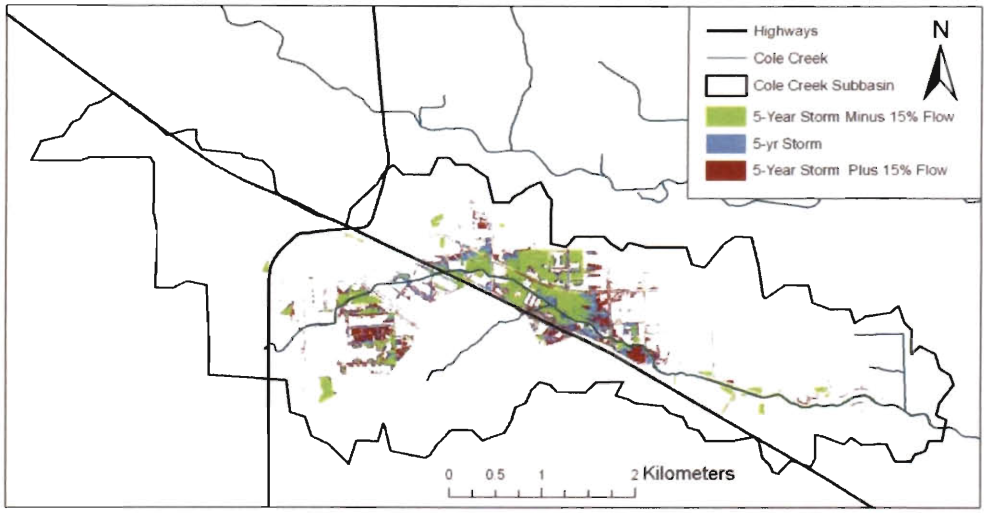


**Figure 15. 2008 5-Year Floodplain Scenarios**

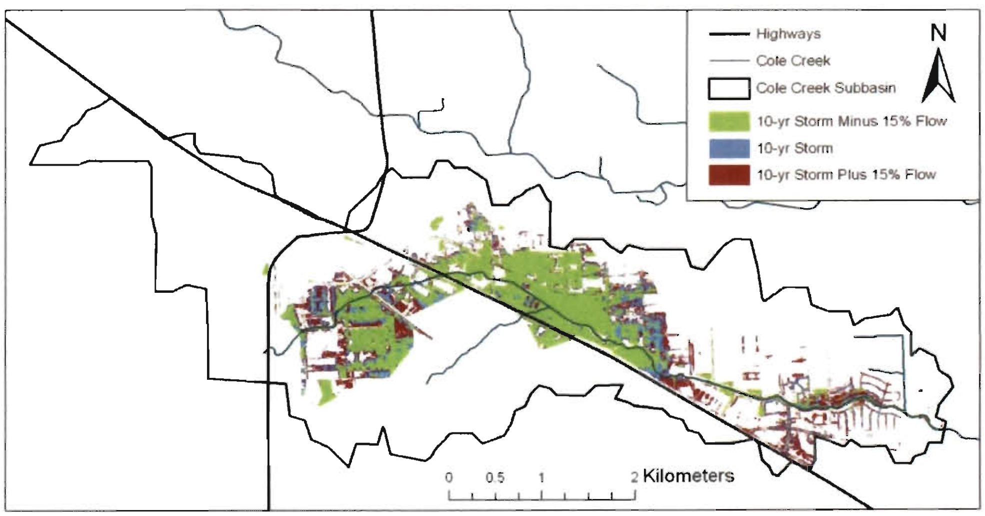


**Figure 16. 2008 10-Year Floodplain Scenarios**

## 4.1. Wetland Loss Scenarios

For this scenario models were created of two hypothetical wetlands conditions: no loss and complete loss. The no loss condition was created by extracting the wetlands from the 1980 model and superimposing them upon the 2008 model. This creates a model in which no wetlands were destroyed from 1980 to 2008. By comparing this model to the 1980 and 2008 models it is possible to see the effect that both general land cover change and wetland loss have had on flood peaks. In the second condition, complete wetland loss, wetlands cells from the Manning's '08 Model were replaced with randomly distributed high and low-intensity development cells. This model has the capacity to show the impact that current wetlands are having on flood peaks.

Both models were then run using 2, 5, and 10-year design storms with an SCS Type III distribution (Table 9). In addition the October 15, 2007 storm was also used as a design storm. An actual storm was used because rain events generally do not follow the hypothetical hyetographs that are used for return storms. The October 2007 storm gives an example of how each development condition may respond under a real event.

**Table 9. 24-Hour Design Storm Cumulative Rainfall (TSARP, 2009)**

| Return Storm | Cumulative Rainfall (mm) |
|---|---|
| 2-Year | 111 |
| 5-Year | 157 |
| 10-Year | 197 |
| 100-Year | 336 |

Output from the 2-year design storm shows that the loss of wetlands has had a sizable impact on 2-year storm peaks over the last 30 years (Figure 17). Wetland loss over this time period has contributed 14 percent of present flood peaks. General land cover development, the difference between the output from the *'08 Land Cover With '80 Wetlands* and the *'80 Land Cover*, has contributed 39 percent to the present peaks. If the remaining wetlands were destroyed, 2-year peaks would be expected to increase by 15 percent. However, despite these changes in peaks flows, the loss of these wetlands does not significantly impact the floodplain (Figure 14).

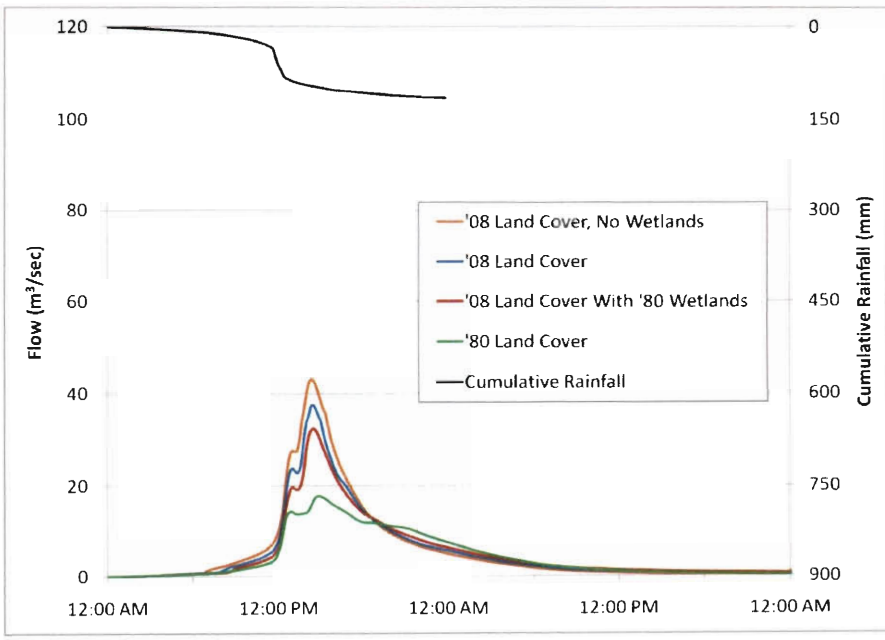


**Figure 17. 2-yr Storm Wetland loss Scenarios**

Outputs from the 5-year storm show similar trends (Figure 18). The loss of wetlands has contributed 13 percent of current peaks flows. If the remaining wetlands were to be destroyed there would be an expected 15 percent increase. The major change in impact between the 2 and 5-year storm is the effect general land development has had on flood peaks, dropping from 39 percent to 12 percent. This is representative of a wetland's ability to retain water at higher flows, while water just runs off most other categories of land cover.

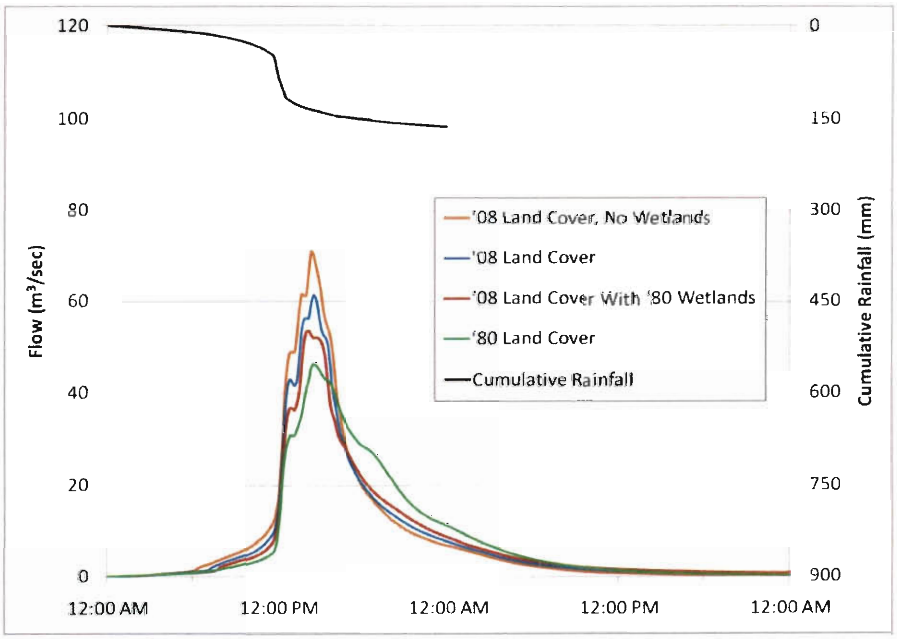


**Figure 18. 5-yr Storm Wetland loss Scenarios**

The contribution of wetland loss on 10-year flood peaks is 13 percent and nine percent for general land development (Figure 19). The expected impact potentially caused by the loss of the remaining wetlands is nine percent. It appears that as flow approaches 10-year levels wetlands still maintain a significant hydrologic presence. However, the impact of remaining wetlands begins to diminish. The impact of general land cover also continues to drop from the 5-year levels.

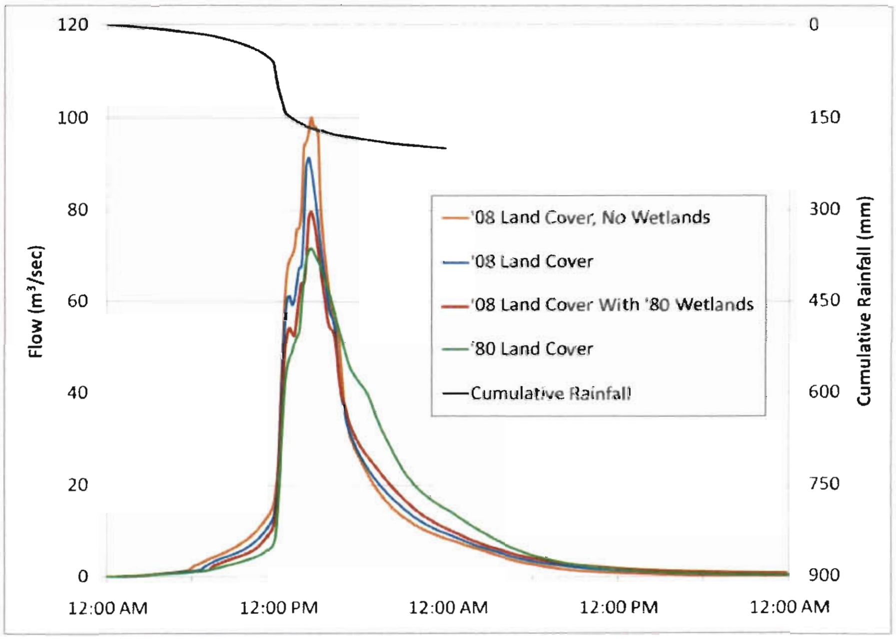


**Figure 19. 10-yr Storm Wetland loss Scenarios**

The results from the October 15, 2007 design storm are nearly identical to those of the 2-year storm (Figure 20). The similarity of these results lends validity to the rest of the results gained from using return storms as design storms.

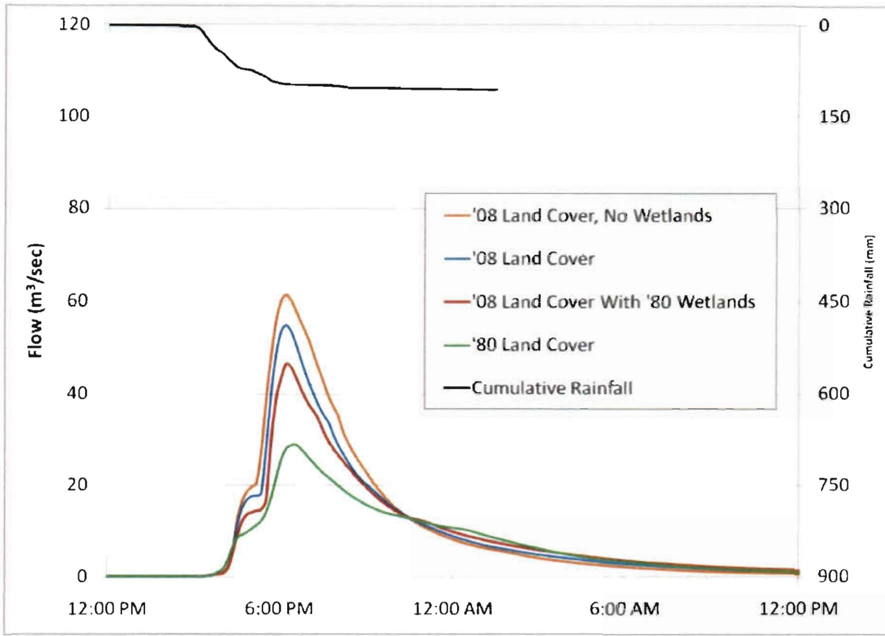


**Figure 20. October 15, 2007 Wetland loss Scenarios**

The results of this analysis show that the historical wetlands in the Cole Creek subbasin made small but significant impacts on 2, 5, and 10-year storms. Though the wetlands destroyed over the past 30 years have contributed about 15 percent to current flood peaks, the existing wetlands have an equally significant impact. As flows increase it seems that the hydrologic impact of wetlands is washed out later than that of general land cover. These finding can be used to optimize future development.

## 4.2. The Impact of Wetland Presence on Localized Flow

Two drainage areas within the subbasin were compared using 2, 5, and 10-year design storms (Figure 21). One drainage area has no wetlands and the other, *Higher Wetlands Zone*, has an area covered by 13 percent wetlands. The *Higher Wetlands Zone*, exhibits higher Manning's roughness values than the *No Wetlands Zone*, but lower slopes and percent imperviousness (Table 10). Both areas have completely loamy soils and thus the same soil parameters.

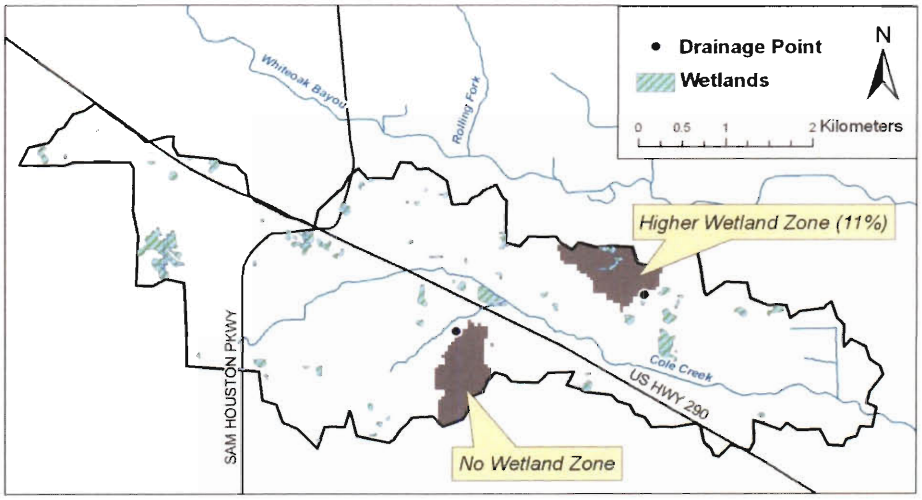


**Figure 21. Wetlands Density Zones**

**Table 10. Wetland Zone Analysis Zone Characteristics Comparison**

| | Higher Wetlands Zone | No Wetlands Zone |
|---|---|---|
| Manning's Roughness | 0.018-0.12 (0.033) | 0.018 |
| Slope | 0.07-2.26% (0.63%) | 0.07-5.22% (0.79%) |
| Imperviousness | 0-68% (36%) | 12-68% (53%) |
| Soil Type | Loam | Loam |

Hydrograph timing from each zone was nearly identical (Figure 22, Figure 23, Figure 24). The presence of wetlands reduced 2-year storm peaks by a third. Five and 10-year storm peaks were reduced by 28 percent.

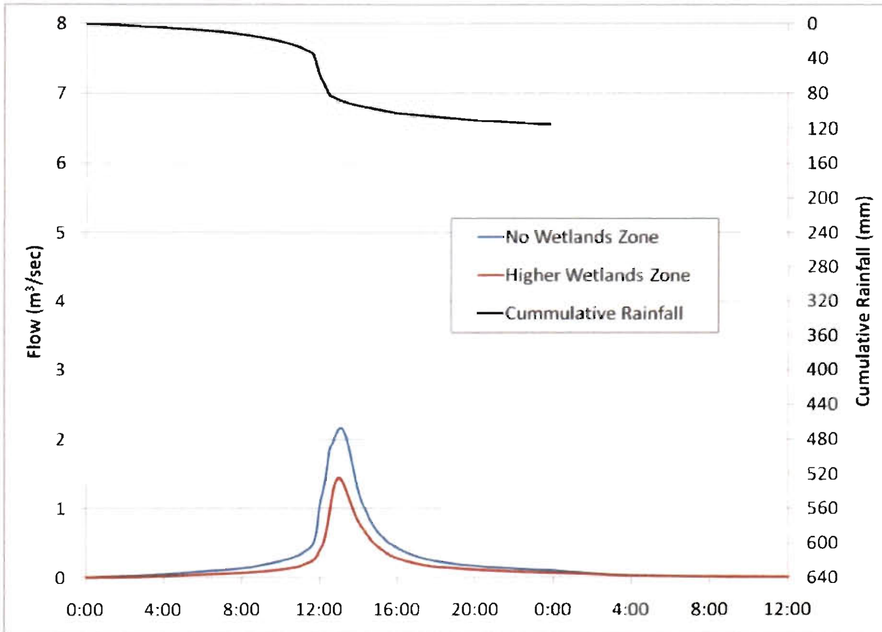


**Figure 22. 2-yr Storm: Wetland Concentration Zone Comparison**

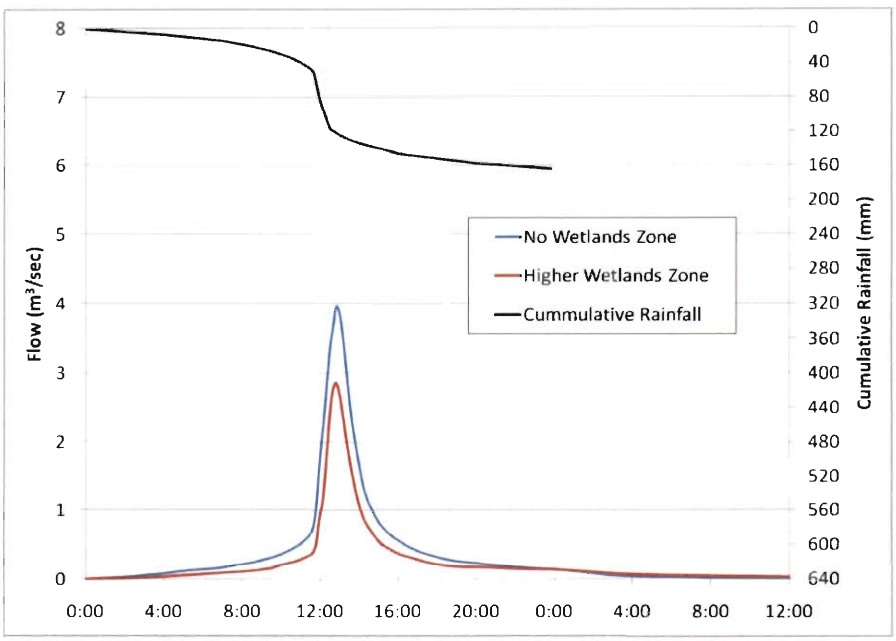


**Figure 23. 5-yr Storm: Wetland Concentration Zone Comparison**

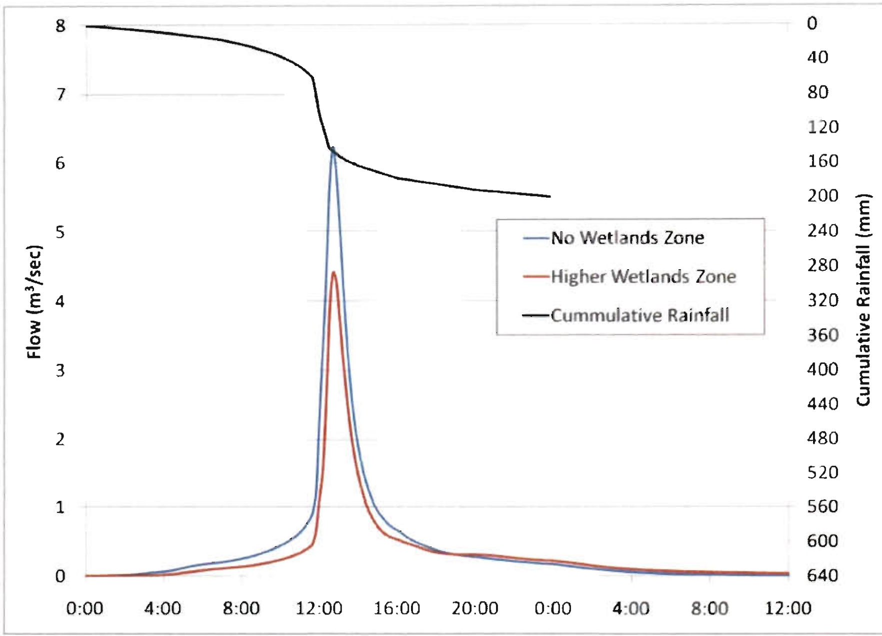


**Figure 24. 10-yr Storm: Wetland Concentration Zone Comparison**

This analysis shows that wetlands can have a high impact on local flood peaks. These results serve a twofold purpose. First, they allow for an isolated look at the effect of wetlands on watershed hydrology. Under the previous analysis, where different scenarios were run on the entire Cole Creek subbasin, the hydrograph was complicated by the arrival of flow from various points within the subbasin at different timing. This timing could mask the effect that wetlands were having, if flow from a high wetland zone arrived at the same time that a nonwetland zone arrived. By isolating each of these zones for analysis it is easier to isolate the effect of wetlands on flood peaks. The second observation that can be extracted from these results is that they allow the user to gain understanding of the effect of wetlands near the subdivision level. In turn this knowledge could be used by regulators and developers to develop best management practices for stormwater runoff at a localized level.

## 4.3. The Impact of Wetland Groups on Flood Peaks

A wetland's position within the surrounding drainage area has an important impact on the wetland's ability to mitigate flood peaks. A wetland that is located on a downstream drainage path of a drainage area has the potential to route a significant amount of flow. This is because downstream areas naturally experience higher flows as they convey runoff from the entire upstream area. These wetlands will henceforth be referred to as gateway wetlands. In contrast to gateway wetlands, wetlands that are located toward the upstream end of a drainage area or are not even a part of a larger drainage area could experience much less runoff. Accordingly, a small gateway wetland could be more hydrologically significant than a large wetland located in the upper end of a larger drainage area.

Gateway wetlands that combine to moderate flow from the same drainage area were analyzed to gain understanding regarding the impact they are having on the subbasin as a whole. The loss of wetlands that do not to serve as gateway wetlands were not considered (**Error! Reference source not found.**). This analysis resulted in indentifying ey existing, flood-mitigating wetlands. Seven wetland groups were identified for this analysis (Figure 25). Flow from a 5-year storm was observed directly downstream of each wetland group. These results were then compared with results supposing the random development of these wetlands into low and high-intensity development. Flow at Deihl Road was also modeled assuming the loss of these wetlands.

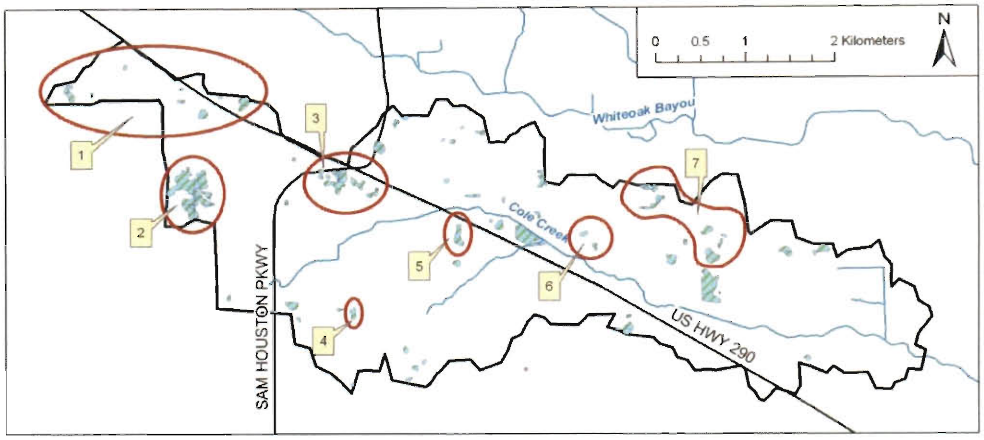


**Figure 25. Wetlands Groups**

As was demonstrated in the comparison of a higher wetland density zone with a no wetland zone, the loss of some wetland groups could drastically increase the flow at a local level (Table 11). Areas downstream of Wetlands Group 1 could experience an 80 percent increase in flow if these wetlands were destroyed. In contrast the effect of Wetlands Groups 3, 4, and 5 is minimal.

**Table 11. The Influence of Wetland Groups on Subbain Peaks During a 5-Year Storm**

| Wetlands Group | Flow at Site ($m^3$/sec) | Projected Flow at Site After Loss ($m^3$/sec) | Projected Change in Flow at Site After Loss | Projected Flow at Deihl Road After Loss ($m^3$/sec) | Projected Change in Flow at Deihl Road After Loss |
|---|---|---|---|---|---|
| 1 | 3.6 | 6.5 | 80% | 64.2 | 4% |
| 2 | 6.0 | 8.4 | 39% | 62.5 | 2% |
| 3 | 3.7 | 4.0 | 6% | 63.5 | 3% |
| 4 | 3.6 | 3.7 | 4% | 61.7 | 0% |
| 5 | 7.8 | 7.9 | 1% | 62.6 | 2% |
| 6 | 4.2 | 4.9 | 16% | 60.8 | -1% |
| 7 | 3.7 | 5.0 | 34% | 64.4 | 5% |

A Wetlands Group that has a large effect on local flood peaks will not necessarily have a large effect on flood peaks at Deihl Road. This is largely due to the fact that the flow contributed by smaller areas within the subbasin are small compared to the combined hydrograph. However, the lack of effect at Deihl Road can also be caused by the complications of hydrograph timing. The effect of the loss of most Wetlands Groups is negligible at Deihl Road. It is interesting to note that though the loss of Wetlands Group 3 does not have a large effect on peak flow locally, it has a comparatively-significant, projected impact on the peak flow at Deihl Road.

Combining some Wetlands Groups (Groups 1-3, 5, and 7) shows the contribution they make as a whole (Figure 26). The loss of all of these Wetlands Groups could lead to a 2-year peak increase of 16 percent, a 5-year peak increase of 15 percent, and a 10-year peak increase of eight percent. Though they only make up 53 percent of the wetlands, the loss of these Wetlands Groups creates peak increases similar to that of the complete loss of all wetlands (Figure 17, Figure 18, and Figure 19). It seems that these Wetlands Groups combined bear the majority of the hydrologic burden in the watershed. With this in mind, Wetlands Groups 1-3, 5, and 7 should be given priority as the future development of Cole Creek is considered. However, it must be considered that flood peaks reduction is only one of the many potential ecosystem services that wetlands provide. Before any wetland is destroyed all services should be considered.

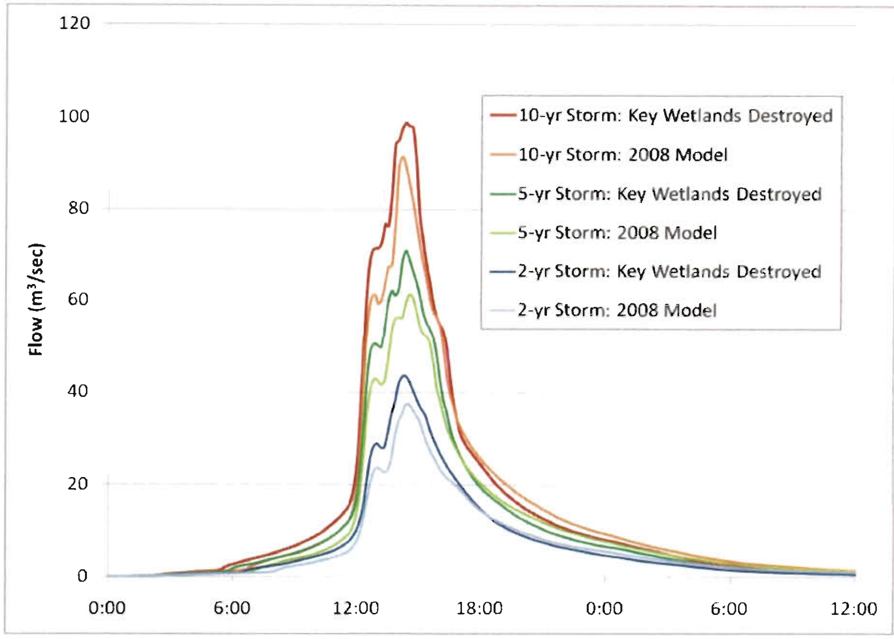


**Figure 26. The Effect of Wetland Group Loss on Flood Peaks**

## 4.4. Optimal Wetland Construction Locations for Flood Mitigation

Six potential locations for wetland construction were identified and analyzed regarding their potential for peak mitigation (Figure 27). These locations were selected because they all serve as the gateway to a larger contributing area that does not already contain a sizable wetland presence. An effort was made to minimize the size of each wetland while still producing a noticeable impact. This resulted in wetlands ranging from 1.0 and 1.3 hectares. An initial smaller wetland size of 0.6 was considered, but this size proved to have no discernable impact locally or subbasin-wide. All six proposed wetlands have a combined area of 7.0 hectares.

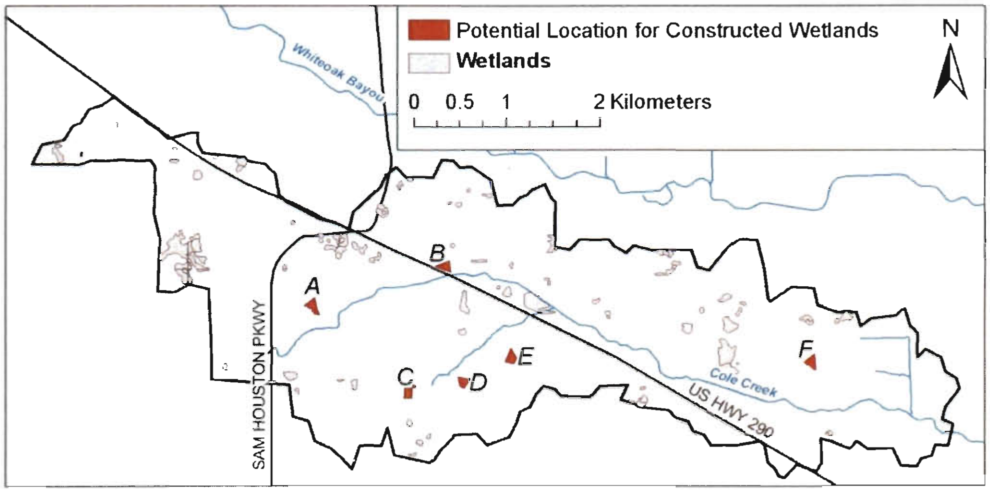


**Figure 27. Proposed Locations for Wetland Construction**

The proposed wetlands would have varying degrees of success at reducing local and regional peaks (Table 12). Wetlands C, D, and E would reduce local peaks by at least 80 percent. Wetlands A and F have practically no effect on local peaks. Most of the wetlands demonstrate minimal success at reducing peaks at Deihl Road individually. However, Wetland E has a much larger potential than the rest to impact peaks at Deihl Road. When the wetlands are combined they have the potential to reduce 5 and 10-year peak flows by approximately 15 percent (Figure 28). Two-year peaks would be reduced by 19 percent.

**Table 12. 5-Year Storm: Projected Changes Due to Wetland Construction**

| Wetland | Contributing Area (ha) | Flow at Site Prior to Wetland Construction ($m^3$/sec) | Projected Flow at Site After Wetland Construction ($m^3$/sec) | Projected Change in Flow at Site | Projected Flow at Deihl Road ($m^3$/sec) | Projected Change in Flow at Deihl Road |
|---|---|---|---|---|---|---|
| A | 82.5 | 9.5 | 9.0 | -5% | 59.8 | -3% |
| B | 53.0 | 3.7 | 2.4 | -35% | 58.2 | -5% |
| C | 51.0 | 3.6 | 0.5 | -87% | 58.9 | -4% |
| D | 21.2 | 2.1 | 0.4 | -82% | 60.2 | -2% |
| E | 45.0 | 3.7 | 0.7 | -82% | 56.3 | -8% |
| F | 166.2 | 4.6 | 4.6 | 0% | 61.5 | 0% |

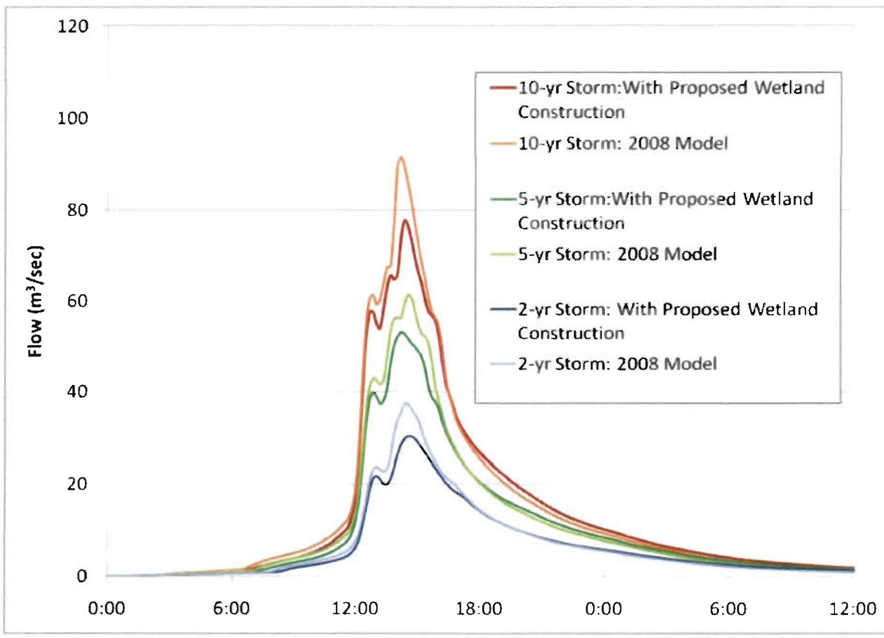


**Figure 28. The Impact of Wetland Construction on Flood Peaks**

## 4.5. Discussion

The combined results from these scenarios give a good understanding regarding the impact that wetlands are having on flood peaks in Cole Creek. The 5-year storm is the key storm in this analysis because wetlands have the potential to cause significant changes in the floodplain, while their impact remains near a maximum. At a subdivision level individual wetlands have the ability to substantially reduce flood peaks at 2, 5, and 10-year levels. As flow increases the impact of wetlands relative to general land cover also increases. However, it is projected that as flows increase beyond the 10-year level the impact of wetlands will eventually become washed out. Small, but strategically-placed, constructed wetlands, could offer significant, future, flood mitigation at the local and subbasin-wide level.

# 5. Conclusions and Future Work

## 5.1. Conclusions

This study has resulted in the development of a practical methodology to assess the subbasin-specific impact of palustrine-wetland loss on flood peaks. The models developed using this methodology could be applied as an effective planning tool. This tool would allow communities to identify wetlands critical to flood mitigation, and potential locations for wetland construction. The methodology was applied to Houston, Texas's Cole Creek. The results from this work could provide a representative case study for many inland areas throughout the world since the wetlands in Cole Creek are distributed throughout the subbasin and make up a percent area similar to the contiguous United States and global average.

The benefit of using a distributed, hydrologic model is that it allows the user to capture the subtle spatial relationships within the subbasin. Wetlands were modeled using both Manning's equation and the Wetlands Power Law. Only by modeling wetlands using the Wetlands Power Law was it possible to get a good match of hydrograph volume, peak flow, and timing. Using Manning's equation required sacrificing one of these three. The results show the impact of wetland loss over the past 30 years has had a similar impact on 2, 5, and 10-year flows, contributing approximately 15 percent to current peaks. However, the remaining wetlands have a similar hydrologic significance to those already destroyed. This study also suggests that as flows increase wetlands maintain a higher hydrologic significance than that of general land cover.

During this study, wetlands critical to flood mitigation were identified within Cole Creek. Individual wetlands proved to be more effective at reducing flood peaks at the local, subdivision level as opposed to subbasin wide. Locations for potential wetland construction were also identified. However, due to the complexities of subbasin timing it is critical that potential wetlands be considered within the larger context of the subbasin. Haphazardly placed wetlands have the potential to increase flood peaks. Also, it should be noted that flood mitigation is only one of the ecosystem services that wetlands provide. Other services should be considered before any planning decisions are made.

## 5.2. Future Work

Since the research in this field is still relatively young, it is replete with potential for future work. The following three paragraphs outline future studies that could naturally follow this thesis.

Though it was not a large setback for this study, addressing the impact of riparian wetlands will be critical if the method is to be applied at a larger scale. Riparian wetlands could be incorporated several ways. First, it would be preferable to find a distributed model that allows the user to vary the modeling technique across channel cross sections. AT the very least it would be necessary to vary Manning's roughness across the cross section. The second option, would be to build a separate hydraulic model, such as HEC-RAS. Though HEC-RAS was used for this study, the model was not built with riparian wetlands in mind. Riparian wetlands could be specifically addressed within HEC-RAS by varying roughness values vertically. This would allow the user to match Manning's Equation with the Wetlands Power Law.

Performing a wetlands study within a more data rich environment would allow for a more detailed understanding regarding individual wetlands and how they affect the larger subbasin. If flow data were gathered from multiple stream gauges within the subbasin, it would allow for each contributing area to be individually calibrated. Flow could also be monitored coming out of a number of wetlands during a variety of rain events. Radar rainfall could be used to provide more spatially accurate rainfall.

Finally, it would be beneficial to scale this study up in two ways: storm size and drainage area. Though it is not expected that the wetlands within Cole Creek have a major impact on large storms, it is these storms that provide the most intrigue. Creating a model specifically calibrated for large storms would allow the user to more accurately assess the impact of wetlands on large storms. Also, scaling up the drainage area to the watershed level would provide insight regarding wetlands impact at a regional level.

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